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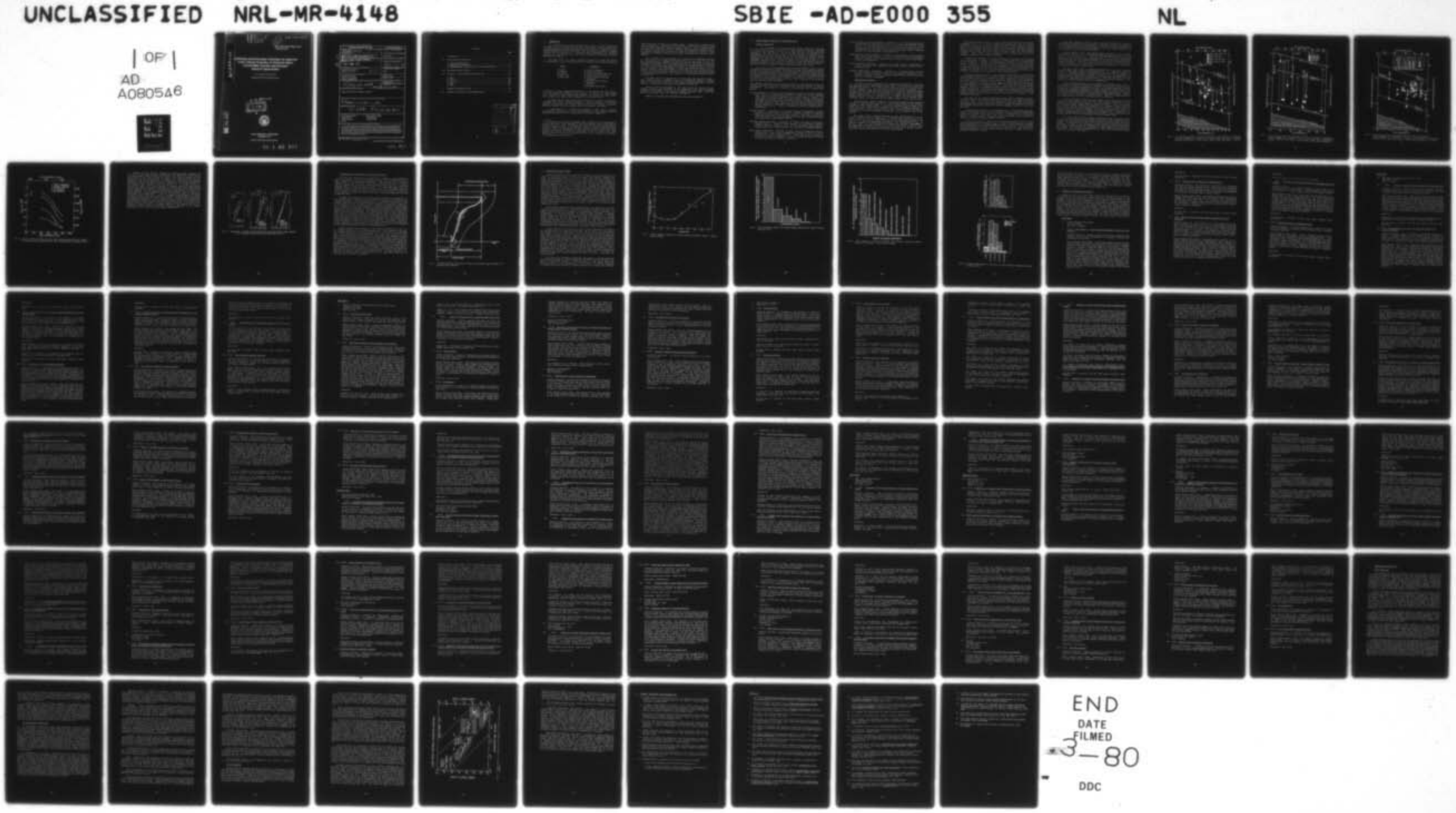

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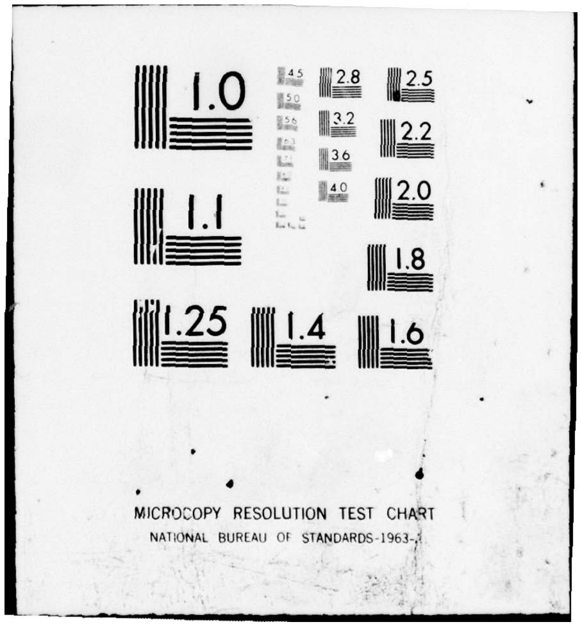
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NRL Memorandum Report 4148
T-TPI/US/4/79

Fabrication and Processing Technology for Improved Crack Tolerant Properties of Structural Alloys: Current R&D Activities and Emergent Research Opportunities

L. R. HETTCHE AND B. B. RATH

Material Science and Technology Division

January 2, 1980

NAVAL RESEARCH LABORATORY
Washington, D.C.

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As a 1978/79 action item, the Metal Panel (TP-1) of The Technical Cooperation Program (TTCP) Sub-Group P initiated a survey on current R&D activities and emergent research opportunities in processing and fabrication technology which show potential to improve the crack tolerant properties of structural alloys. This action was in response to repeated requests from the Sub-Group P for information and recommendations for Sub-Group activities in this general area. The U.S. contribution to this survey is documented in this report.

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Contents

I. INTRODUCTION

As a 1978/79 action item, the Metal Panel (TP-1) of TTCP* Sub-Group P initiated a survey on current R&D activities and emergent research opportunities in processing and fabrication technology which show potential to improve the crack tolerant properties of structural alloys. This action was in response to repeated requests from the Sub-Group P for information and recommendations for Sub-Group activities in this general area. The U.S. contribution to this survey is documented in this report.

The scope of the U.S. survey includes a synopsis of current R&D efforts for various pairs of the following structural alloys and crack tolerant properties:

Alloys	Properties
• steels	• fracture toughness
• aluminum	• fatigue resistance
• titanium	• corrosion fatigue resistance
• nickel base	• creep fatigue resistance
• cobalt base	• stress corrosion cracking resistance
	• sustained load cracking resistance
	• fretting
	• hydrogen embrittlement

In addition, the newly emergent techniques of ion implantation and laser processing were identified specifically for review. The purpose of these reviews is to ascertain to what extent these processes and methods have shown potential to improve the crack tolerant properties of structural alloys.

Excluded from this survey were R&D activities on alloys not listed above, including metal matrix composite materials. Moreover, because of limitations imposed on the survey, the closely related survey inputs received on fracture mechanics analyses and test procedures were not included in this report.

In anticipation of a cosmopolitan readership of this report, including new initiates to the subject of crack tolerant behavior of high strength alloys, a background description of this problem area is provided in Chapter II.

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*The Technical Co-operation Programme (TTCP) originated from a Declaration of Common Purpose made by the President of the United States and the Prime Minister of Great Britain in 1959. The United States and United Kingdom were joined by Canada and later Australia and New Zealand. Through a number of Sub-Groups, TTCP provides a means of acquainting the participating countries with each others Defense R&D programs and promotes concentrated action to identify and close important gaps in the collective technology base, which includes pure research.

Note: Manuscript submitted November 27, 1979.

These discussions include the following topics: definitions of various crack tolerant properties; representative data showing the relationship between strength, crack tolerant properties, and environmental effects; and a phenomenological description of the failure processes. Although this background information serves as a general introduction to the subject, these discussions also provide a useful framework for subsequent sections of the report and should be of interest to most readers.

One of several sources exercised in the collection of information and data for this report was a computer literature search for the years 1968 to 1978. Here, publications were enumerated by years for various combinations of alloys and properties listed above. The time frame allowed for this survey and the magnitude of number of pertinent papers published during this period combined to preclude even a printout of this bibliography, let alone any systematic search of such a listing. However, these data provide a useful measure of the distributions and trend of U.S. efforts and are indicative of the vast R&D resources being applied to this pervasive problem area. The statistics of this computer research is given in Chapter III.

The major source of information for this survey was obtained through a direct mailing inquiry to members of the U.S. material R&D community, including those of the Army, Navy, Air Force, DARPA, NASA, and IR&D participate in private industry. A synopsis of these inputs is provided in Chapter IV.

Chapter V provides highlights of the survey as well as reviews of newly emergent processes and techniques of ion implantation and laser processing. Information for Chapter V was obtained through literature search, solicited inputs, and personal contact of cognizant investigators.

Summary, Conclusions and Recommendations are given in Chapter VI.

II. CRACK TOLERANT PROPERTIES OF STRUCTURAL ALLOYS

Property definitions

It is axiomatic in the sophisticated, highly competitive technology of defense hardware that our ability to supply improved structural materials in a timely and affordable way will be an important factor in determining the performance, cost, and safety of future military vehicles and platforms. Notwithstanding the positive gains made in the utilization of advanced organic composite materials over the past decade and the optimistic forecast for the development of metal matrix composite materials over the next decade, it is a reasonable assumption that the vast majority of high performance structural material utilized in both military and private sector will be derivatives of the current ferrous, aluminum, titanium, nickel and cobalt base alloys.

It is also an accurate statement that the major technical issue in either the improved development or optimum utilization of these alloys systems is related to their crack tolerant behaviors. As is well known, the structural efficiency of alloys and weldment systems is directly proportional to allowable design stresses at which these materials can be incorporated into a structure. The design stresses for commercial high strength alloys, however, are typically a fraction ($\sim$ 1/4 to 1/2) of the yield strengths which in turn are only a fraction of the strengths which are metallurgically obtainable.

The seemingly conservative (low) working stresses of high strength alloys are dictated by their subcritical crack growth and fracture behavior in service environments. This behavior is defined by the following crack tolerant properties:

Fracture toughness: "A generic term for measures of resistance to crack extension. NOTE - The term is sometimes restricted to results of fracture mechanics tests, which are directly applicable in fracture control. However, the term commonly includes results from simple tests of notched or precracked specimens not based upon fracture mechanics analysis. Results from tests of the latter type are often useful for fracture control, based upon either service experience or empirical correlations with fracture mechanics tests." Proposed definitions - (ASTM - Subcommittee E24.05 on Nomenclature & Definitions).

Fatigue resistance: resistance to "the process (fatigue) of progressive localized permanent structural change occurring in a material subjected to conditions which produce fluctuation stresses and strains at some point or points and which may culminate in cracks or complete fracture after a sufficient number of fluctuations," (ASTM Standard E206-72).

Corrosion fatigue resistance: resistance to "fatigue aggravated by corrosion" (Standard E6-76). "Corrosion is the chemical or electrochemical reaction between a material, usually a metal, and its environment that produces a deterioration of the material and its properties," (Standard G15-76).

Creep fatigue resistance: resistance to joint action of fatigue and creep or creep rupture. Creep is the time-dependent increase in strain in a solid resulting from force (Standard E6-76). "Creep rupture is a process of progressive localized permanent structural change produced in solids by creep culminating in cracking and fracture."

Stress corrosion cracking resistance: resistance to "a cracking process (SCC) that requires the simultaneous action of a corrodent and sustained tensile stress. This excludes corrosion-reduced sections which fail by fast fracture. It also excludes intercrystalline or transcrystalline corrosion which can disintegrate an alloy without either applied or residual stress," (Standard G15-76). See also definition of corrosion above.

Sustained load cracking resistance: resistance to time-dependent crack propagation under load in the absence of creep or corrosion and other environmental effects. Sustained load cracking includes intrinsic hydrogen embrittlement in pre-cracked materials.

Fretting fatigue resistance: resistance to fatigue caused or aggravated by slight oscillatory slip (rubbing) between solid surfaces held in contact by normal force.

Hydrogen embrittlement resistance: resistance to "hydrogen-induced cracking or severe loss of ductility caused by the presence of hydrogen in the metals," (Standard G15-76). Hydrogen embrittlement without external sources of hydrogen is intrinsic.

Representative Behavior

In order to place in perspective the engineering significance of the crack tolerant properties for high strength alloys, Figs. 1 thru 3 have been constructed. Here measured values of the critical stress intensity factors for plane strain fracture toughness, K_{IC}, and for stress corrosion cracking thresholds, K_{ISCC}, of three classes of alloy have been plotted as a function of the measured yield strengths and the calculated critical depths for a thumb nail crack in a large, unaxial stressed plate. In accordance with the fracture mechanics relationship between stress and critical crack depths, ($K_{IC} \sim \sigma \sqrt{dc}$), loci of constant stress intensity factors are shown as line of constant slope on these log-log plots.

The plane strain fracture toughness is a material-toughness property measured in terms of stress-intensity factor of a linear elastic medium by the procedure reported in ASTM Standard E399. In this test procedure, K_{IC} is based on the lowest load, that is lowest stress intensity, at which a significant extension of the crack occurs. Hence, the K_{IC} points of Figs. 1 thru 3 indicate the critical crack depths at which the hypothetical flawed plate will fail under a yield stress loading.

The stress corrosion cracking threshold of a high strength alloys is a crack tolerant property which is measured by the minimum stress intensity factor for which a crack will exhibit measureable but usually subcritical growth in the presence of a specified aggressive environment. The determination of K_{ISCC} is made by a number of non-standardized test methods and specimen configurations. The K_{ISCC} data, therefore, indicate the critical crack depth at which a crack will grow when the hypothetical flawed plate is emersed in an aqueous solution, typically 3.5% NaCl, and subjected to a yield stress loading.

The data sets shown in Figs. 1, 2 and 3 were abstracted from the literature (references 1, 2, 3 & 4) and are considered representative, but by no means definitive, examples of the crack tolerant behavior of these important class of alloys - α/β titanium, martensitic steel, and precipitated hardened aluminum. Hence, no quantitative conclusions should be inferred from these data analyses although several broad brush trends can be observed. Namely, the crack tolerant behavior of these alloys is seen to depend on their strength and is seen to be extremely sensitive to the aqueous environment.

Through heat treatment, the yield strength of these alloys can be varied over a wide range of values. Increases in strength, however, are accompanied on the average by a greater than proportionate decrease in the plane strain fracture toughness. Because of square dependence of the critical crack size on K_{IC}, the fracture susceptibility of a component is disportionately increased as the yield strength of the alloy and/or operating stress are increased. For example, the critical crack size for the analyses of Figs. 1, 2 and 3 decrease by an order of magnitude over the ranges of yield strength examined.

The K_{ISCC} values of Figs. 1, 2 and 3 define defect depths for crack growth in an aqueous environment to be anywhere from 2 to 100 times smaller than the critical crack sizes for fast fracture in identical materials. Of the data shown, this effect is most pronounced in the martenistic steels and the Ti-8Al-1Mo-IV. It is of interest to note that the low K_{ISCC} of Ti-8Al-1Mo-IV alloy gave cause for investigators of a leading aerospace firm to pronounce this alloy as obsolete in 1972 (reference 4). Although the use of this alloy has not been without problems, this alloy has remained a useful structural alloy, particularly in gas turbine applications. The authors would suggest the continued use of this alloy as well as other SSC sensitive alloys is a result of the incorporation of fracture mechanic analyses in the design, fabrication, and inspection schedules of high performance structures.

The data for two recently developed alloys, NAVAIR's CORONA-5 (Ti-4.5Al-5Mo-1.5Cr) and Air Force's AF1410 steel (Fe-14Co-10Ni-2Cr), are shown respectively in Figs. 1 and 2. Both alloys were developed to meet the needs of aerospace applications based on fracture mechanic design criteria (see references 5 and 6) and represent significant increase in fracture toughness relative to these 1972 data bases.

A discriminating feature of the aluminum data is a well defined anisotropic behavior of the plane strain fracture toughness. The K_{IC} values are consistently ordered with respect to the directions of crack orientation in the rolled plat products. These variations in K_{IC} and associated critical crack size must be taken in the design of high performance structure.

Also shown in Figs. 1 thru 3 are the reported ranges of the so called fatigue stress intensity thresholds, K_{TH}, for which fatigue cracks will initiate. The corresponding size of threshold flaws are seen to be several orders of magnitude smaller than the critical crack size for fast fracture, and in fact, the continuum assumptions of linear elastic fracture mechanics is suspect when extrapolated to this size of defect.

These data analyses of Figs. 1 thru 3 not only illustrate the range in defect and crack sizes, some three orders of magnitude, which must be considered in the design, fabrication, and inspection of structures of high strength alloys but also make clear the engineering necessity of setting design allowables for these alloys well below their yield strength.

Another example of the relationship between strength and crack tolerant properties is the data for a precipitation hardened stainless steel (17-4 PH) shown in Fig. 4 (reference 7). This alloy has been utilized for specialized purposes in aircraft and rocket components and in certain marine applications like sturts and foils for hydrofoils because of the alloys relatively good corrosion resistance. The data of Fig. 4 show the effects of electrochemical potential coupling on the stress corrosion cracking resistance of this alloy, heat treated to various strength levels.

The upper curve of Fig. 4 illustrates the decrease in K_{ISCC} for increasing strength levels under freely corroding conditions. The lower curves show the effects of increasing negative electrochemical potential when the specimen is coupled to the following anode materials: aluminum, zinc and magnesium. The coupled materials are similar to anodes used in corrosion protection of marine structures. Reportedly, the decrease in K_{ISCC} with negative potential is the results of increased hydrogen activity at the crack tip.

If the positive direction of the horizontal and vertical axes of Fig. 4 are equated to increased performance (strength) and increased structural reliability (crack tolerance) respectively, and if the increasing negative potential is equated to decreasing maintenance (corrosion protection), these data not only indicate the engineering significance of crack tolerant properties but also show the material selection trade-offs confronting the structural designer. Namely, what combination (or window) of variables in Fig. 4 offers the optimum balance of performance, safety, and cost for specified service conditions.

A final but perhaps the most important example of the engineering limitations imposed on high strength alloys by their crack tolerant properties is their fatigue and corrosion fatigue behavior. Recall from Figs. 1 thru 3 that fatigue and corrosion fatigue loading are responsible for initiating cracks from very small, usually surface or near-surface defects, of a material. Unlike the fracture toughness and SCC behaviors, however, the fatigue crack-growth resistance of structural alloys is relatively insensitive to strength level. Nonetheless, the fatigue loading determines the allowable design stresses in many applications and, thereby, preclude the use of alloys above a certain strength level.

The characteristic material property describing fatigue crack-growth resistance is the per-cycle crack growth da/dN as a function of the fracture mechanics parameter ΔK, the magnitude of the stress intensity excursions during the cyclic loading. In addition to its utility as a direct measure of fatigue crack growth resistance, the da/dN vs. ΔK relationship can be used to predict service behavior and, thereby, prevent failure by containment of crack growth within quantitative safe limits. The rationale and methodology for using fracture mechanics fatigue design are discussed in reference 8.

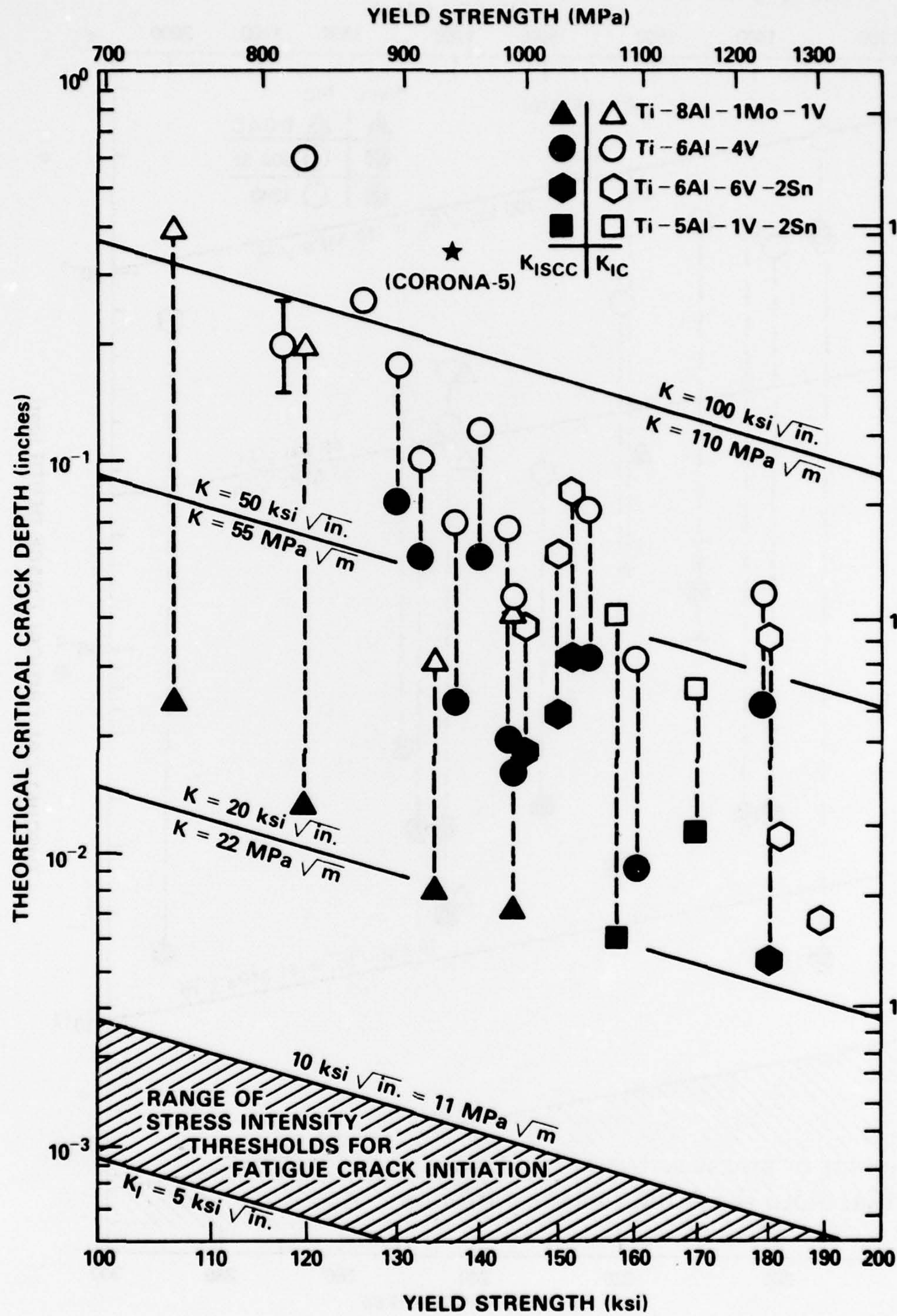

Fig. 1 K_{IC} and K_{ISCC} data for α/β Titanium alloys are plotted as function of yield strength and theoretical critical crack depth for a uniaxial stressed plate under a yield stress loading (data from Refs. 1, 2, 3).

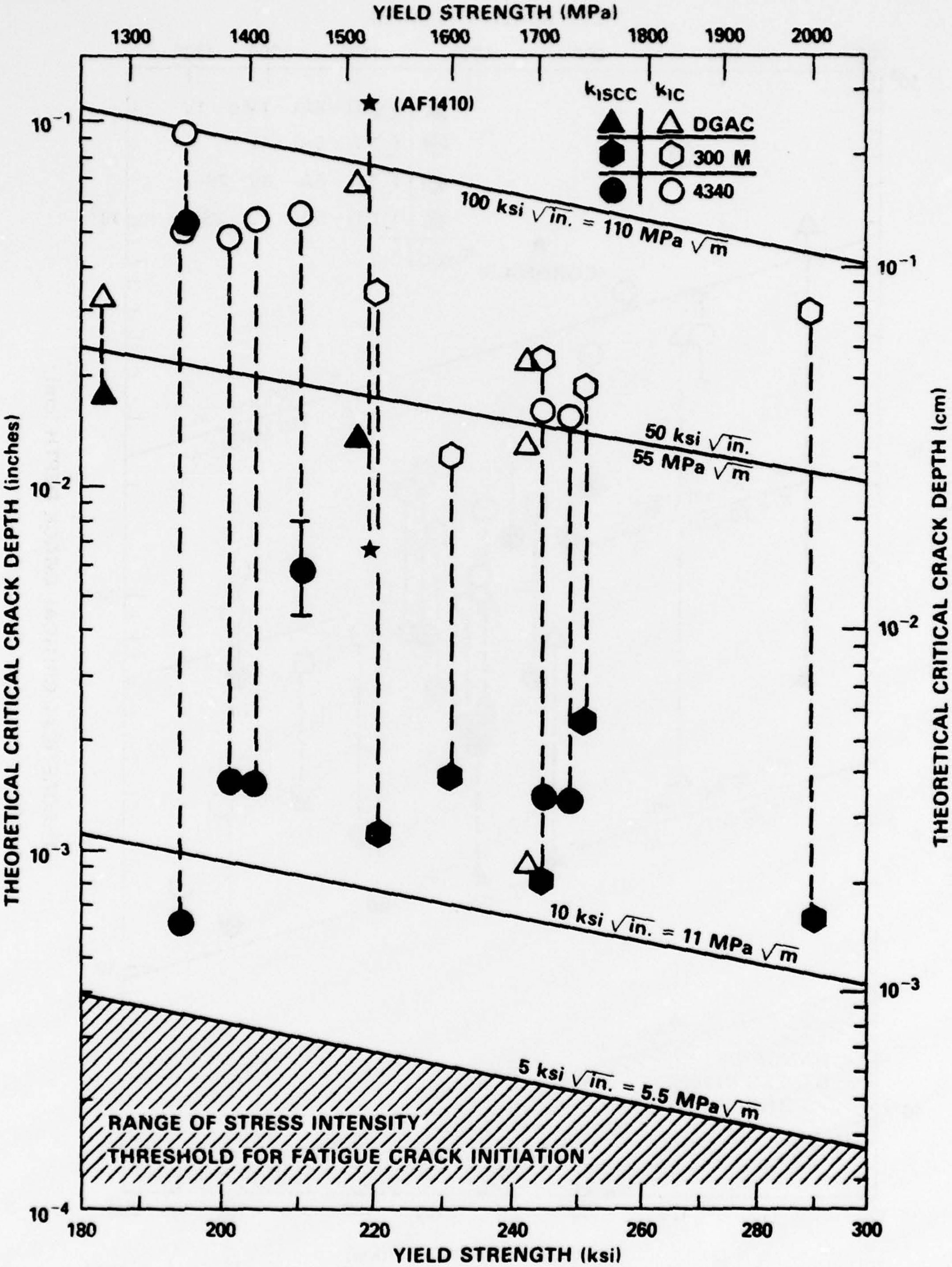

Fig. 2 K_{IC} and K_{ISCC} data for martensitic steels are plotted as function of yield strength and theoretical critical crack depth for a hypothetical uniaxial stressed plate under a yield stress loading (data from Refs. 1, 2, 3).

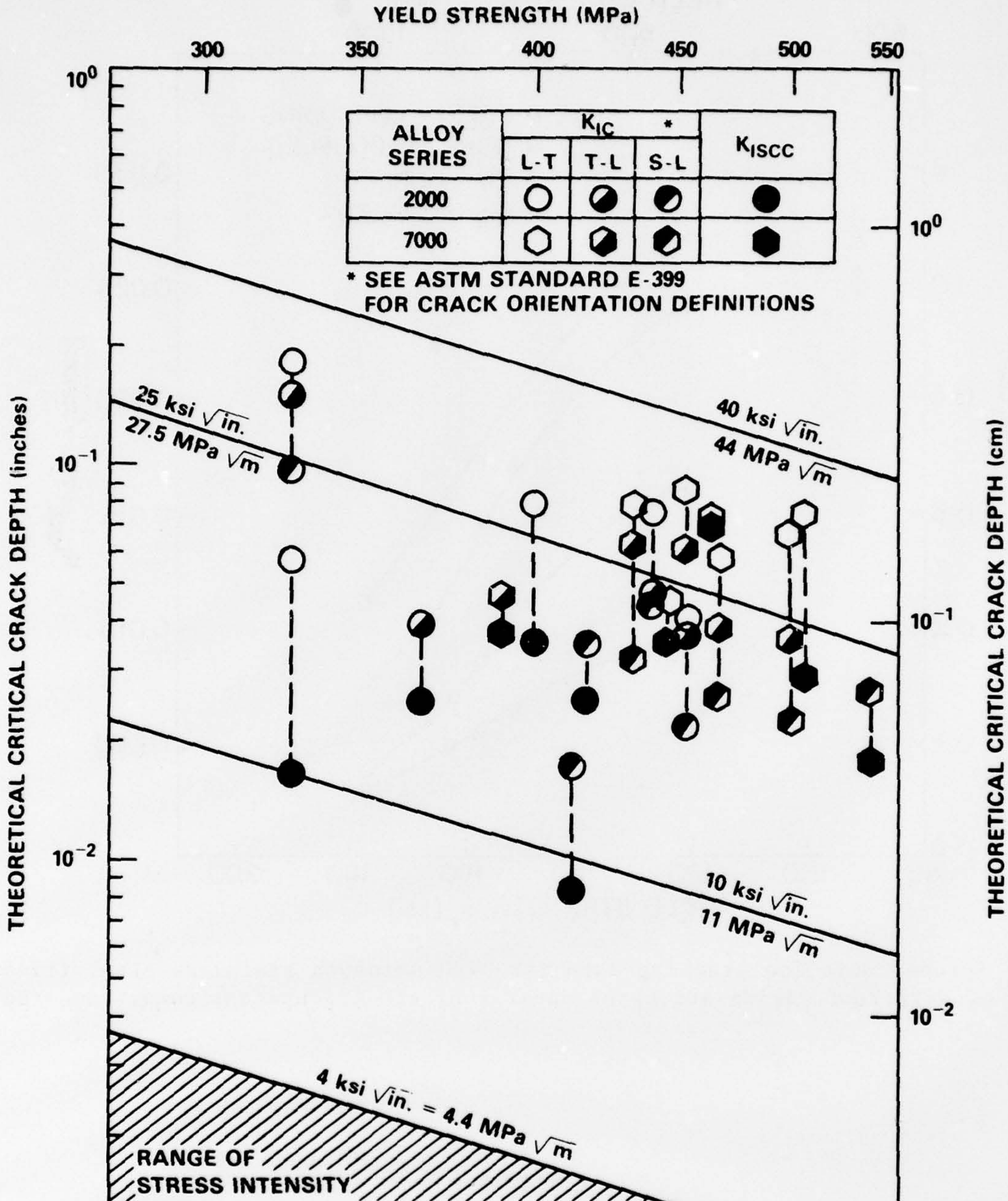

Fig. 3 K_{IC} and K_{ISCC} data for aluminum alloys are plotted as function of yield strength and theoretical critical crack depth for a uniaxial stressed plate under yield stress loading (data from Refs. 1, 2, 3, 4).

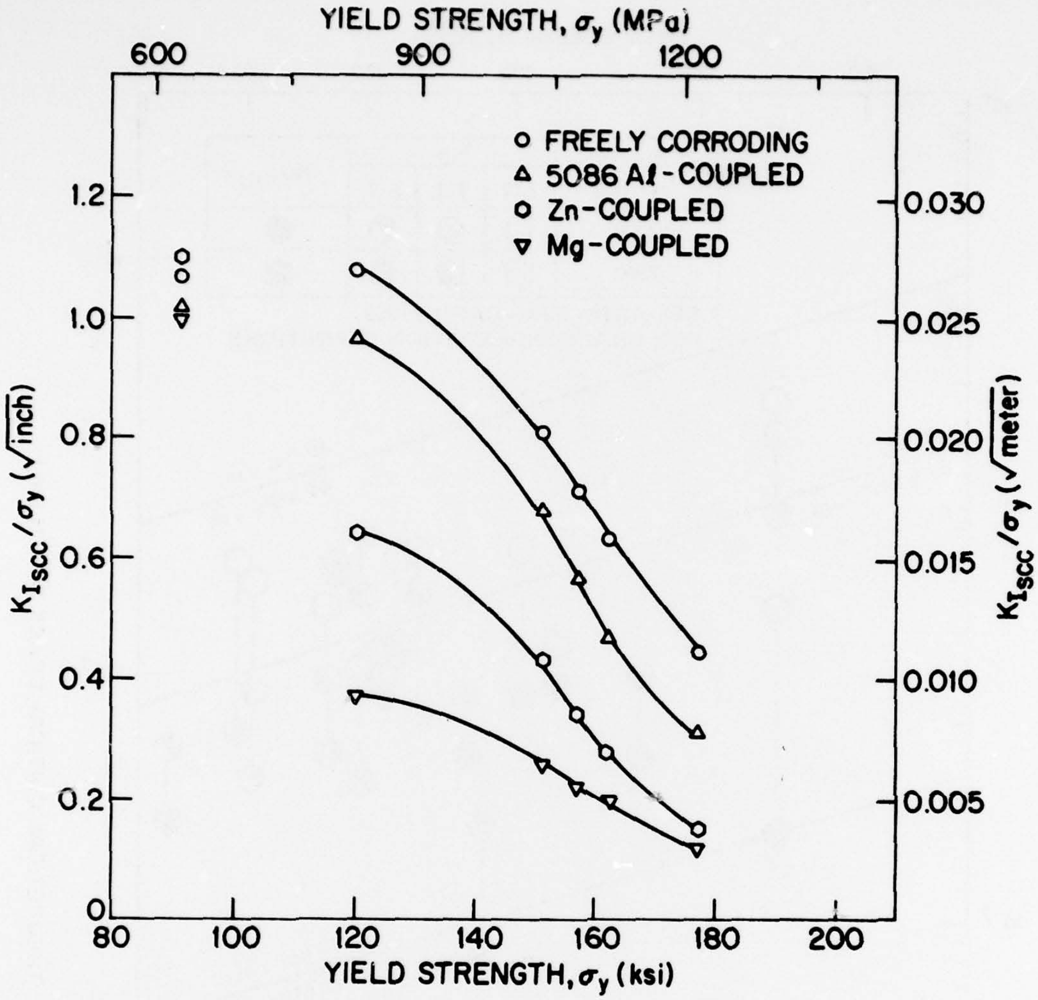

Fig. 4 Stress corrosion cracking data for high strength stainless steel (17-4PH) of different yields strengths under four electrochemical conditions (Ref. 7).

Although fracture mechanics methods of predicting fatigue behavior are now used in the design process, understanding the mechanical, metallurgical, and electrochemical factors affecting fatigue crack growth resistance and the translations of this understanding to improve or to optimize alloys has only begun to be explored and exploited. For example, the varied effects of seawater environment and electrochemical potential coupling on the fatigue behavior of three marine alloys are shown in Fig. 5 (reference 9). In the case of the 17-4 PH stainless steel, seawater environment and negative potential significantly decrease the fatigue crack growth resistance of this material. The marine aluminum alloy (5456-H116) also exhibits a deleterious effect of seawater on fatigue crack growth behavior; but both negative and positive potential from the freely corroding potential of approximately -1.0V have the beneficial effect of decreasing the fatigue crack growth rate. In fact, a fatigue crack growing in the freely corroding condition has been observed to be abruptly terminated when the specimen was polarized cathodically to -1.4V (reference 10). The basic electrochemical and micromechanical processes controlling these phenomena, as well as the engineering ramifications of these results, are not now well understood. In contrast to the ferrous and aluminum alloys, the fatigue behavior of the titanium alloy is not affected by either seawater or negative potential, attesting to the superior performance of this class of alloys in marine applications.

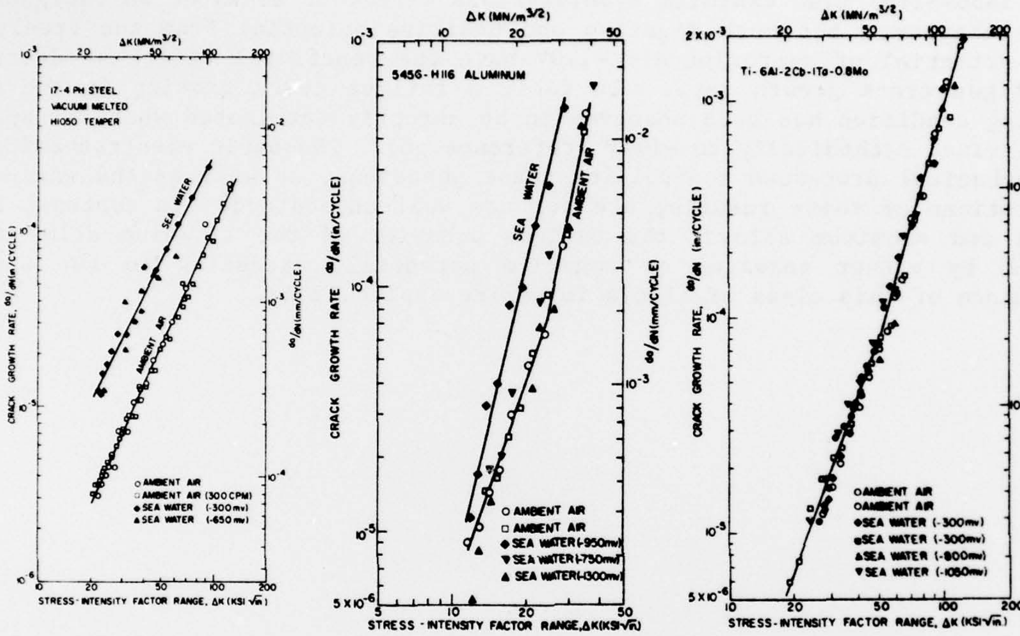

Fig. 5 Comparison of fatigue crack growth data for three alloys under ambient air, seawater and potentiostated conditions (Ref. 8).

Phenomenological Description of the Failure Process

With the above discussion as an introductory background, a simple phenomenological description of the failure process in these alloys is provided now as a useful framework for subsequent discussions. This description is illustrated schematically in the crack size versus time relationship of Fig. 6. Here a crack is hypothesized to initiate from some small surface defect of a fabricated component after a required incubation time. The crack then grows under the combined influence of mean and cyclic loading as well as environmental influence; fast fracture occurs when the crack has grown to a critical depth. The life time of the component is seen to be equal to the sum of the crack incubation and crack propagation times.

Although this description of the crack growth process is oversimplified, it does manifest several important technical issues in the quest for improved crack tolerant properties of high strength alloys. The efficient utilization of high strength alloys requires an accurate description, that is a predictive capability, of all phases of the crack growth process - initiation, propagation and fracture. Such a capability is not only required for optimum utilization of high strength alloys but also for determining the safe and economical inspection and maintenance schedules of critical components. For example, the design of gas turbine rotor disk is based on a crack initiation criteria. However, given a finite probability that a crack will initiate, it must be ascertained that the crack will not grow to a critical size during the inspection period for that disk. This example illustrates the need to examine the tradeoff of properties in the process and fabrication optimization of any one crack tolerant property. For example, although it is very desirable to improve the crack initiation resistance of gas turbine disk alloys, improvements in this property at the expense of increased crack propagation or lower fracture toughness may well be counterproductive.

Another technical issue implicit in the lifetime description of Fig. 6 is the measured variation in crack tolerant properties. Such effects are indicated by a nominal distribution for crack incubation (t_o) time and critical crack depth (d_c). Wide variation in these properties, e.g., K_{TH} or K_{IC}, as well as other crack tolerant properties are observed. For example, it is not uncommon to measure factor of 2 variations in these properties for different heat of an alloy and 30-40% variation for specimens taken from the same heat. Ostensibly these variations are attributed to any one or combination of variables, including alloying and structure sensitivities of crack tolerant properties which are not controlled by standard processing specifications, inhomogenous variations in processed product forms, and non-reproductable property test methods. The important point here is that elimination of these variations for whatever cause has the same benefit as improving the specific property an equivalent amount. Moreover, because of the high cost of measuring crack tolerant properties, the large number statistics of these data are not generally available.

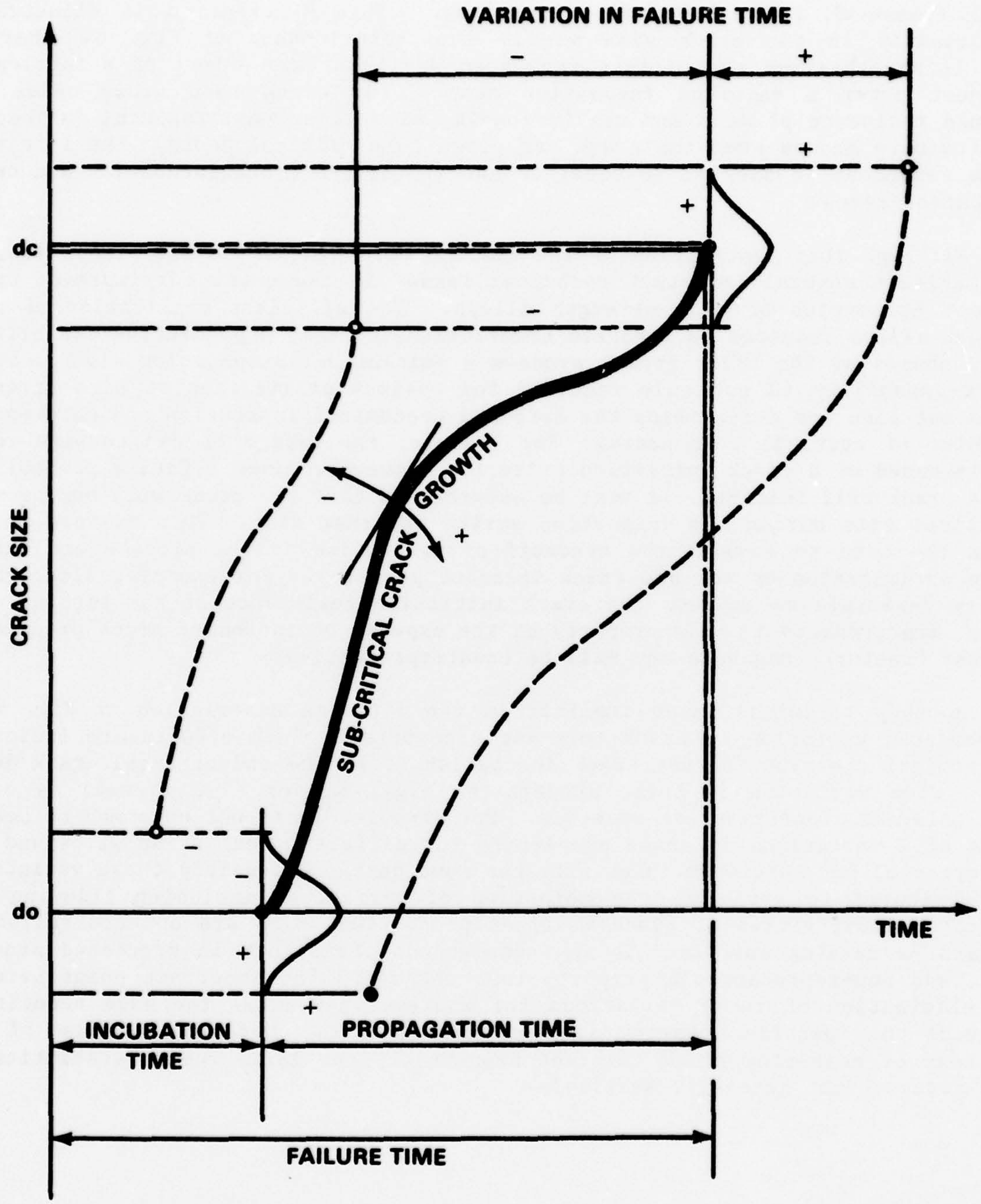

Fig. 6 Phenomenological description (crack size versus time) process in a strength alloy component.

III. PUBLICATIONS DATA & TRENDS

Since the recognition of the importance of damage tolerant properties to the design of structures, research effort on this subject has steadily increased every year. As illustrated in Fig. 7, a total of about 1,300 citations related to all damage tolerant properties published in the years 1969 or in 1970, increased to over 2,100 citations in 1977. In 1978 this number has been exceeded although the abstract compilation for '78 is not complete as of this writing. These citations have been compiled from the metals abstract index. Although the numbers referred to in this report are related to the number of publications in open literature, due to the nature of the indexing system publications concerned with more than one crack tolerant property has been accordingly counted more than once. The emphasis on these studies are nearly proportional to the total annual consumption of structural alloys as illustrated in Fig. 8. These alloys are divided into five different categories: steels, aluminum alloys, titanium alloys, nickel alloys and cobalt alloys. Research citations of steels during the last 9 years was in excess of 9,500 papers whereas the next alloy in order of usage was covered in 2,300 papers. The number of publications on Ti and Ni (1,300 on Ti and 700 on Ni) were significantly lower.

Crack tolerant properties were identified under nine categories. The order of their relative relevance to structural design can be directly related to the number of publications on each category. The categories listed in order are: (1) Fatigue-life, (2) Fracture toughness, (3) Stress corrosion cracking, (4) Hydrogen embrittlement, (5) Corrosion fatigue, (6) Fatigue crack initiation, (7) Creep-fatigue interaction, (8) Fretting fatigue and lastly (9) Sustained load cracking. These findings are shown in Fig. 9. The number of publications in fretting fatigue and sustained load cracking are increasing at a fast rate. Lack of test standardization has been one of the difficulties in the areas of fretting fatigue and sustained load cracking investigation. From the present trends it is expected that the last three categories will receive increased research attention.

A major fraction of the research in crack tolerant properties are funded by DoD through three of its branches, Army, Navy, and Air Force. Over 700 projects are currently active in these areas. The Navy and the Air Force carry about an equal number of projects (Navy 270 and Air Force 295) and the Army is supporting about half that number (Army 125). Research topics related to corrosion fatigue, stress-corrosion cracking, hydrogen embrittlement and creep-fatigue interaction is emphasized in the Navy programs, which has traditionally taken the leadership role in these research areas. Air Force, over the last 5-7 years has increased its research emphasis on fatigue, fracture toughness and creep-fatigue interaction. The new thrust areas dealing with fretting fatigue and sustained load cracking is now being equally recognized by the Navy and Air Force R&D community. Army's committment has been primarily in the field of fatigue, fracture toughness and stress-corrosion cracking. Aluminum and titanium alloys has in the recent past received increased DoD research emphasis over that for steels. These data are shown in Fig.10.

The science and technology dealing with new methods of surface protection and coating has recently received significant attention from the materials community. Publications related to 1,040 citations on this subject during the last nine years is a clear indication of the new thrust. The surface protection of aluminum alloys has received the maximum attention in this area (355 citations)

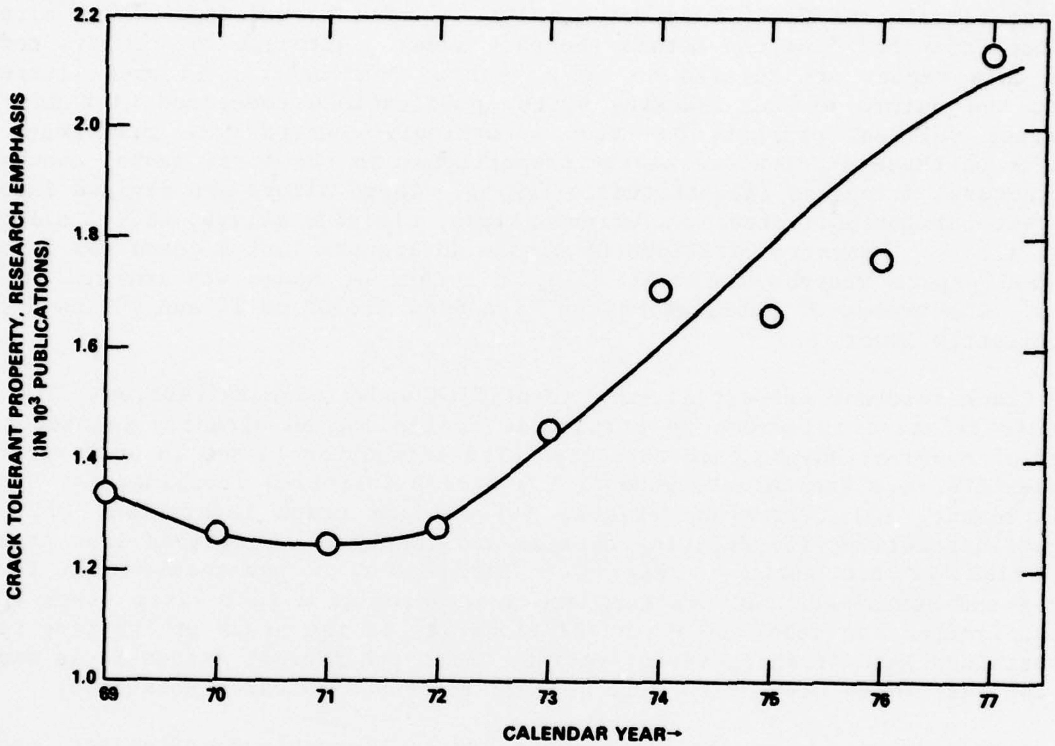

Fig. 7 Yearly Research Citations in Crack Tolerant Properties (Source: Metals Abstract Index).

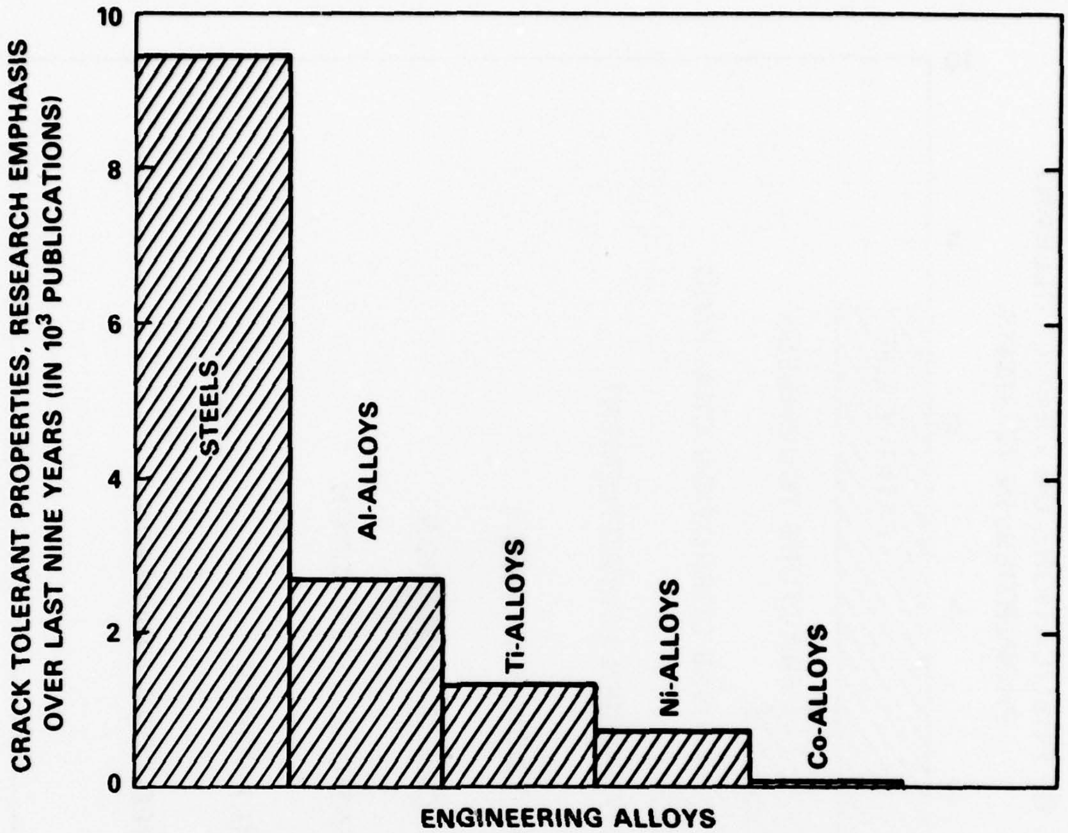

Fig. 8 Total Research Citation for Alloys between 1966 and 1977 (Source: Metals Abstract Index).

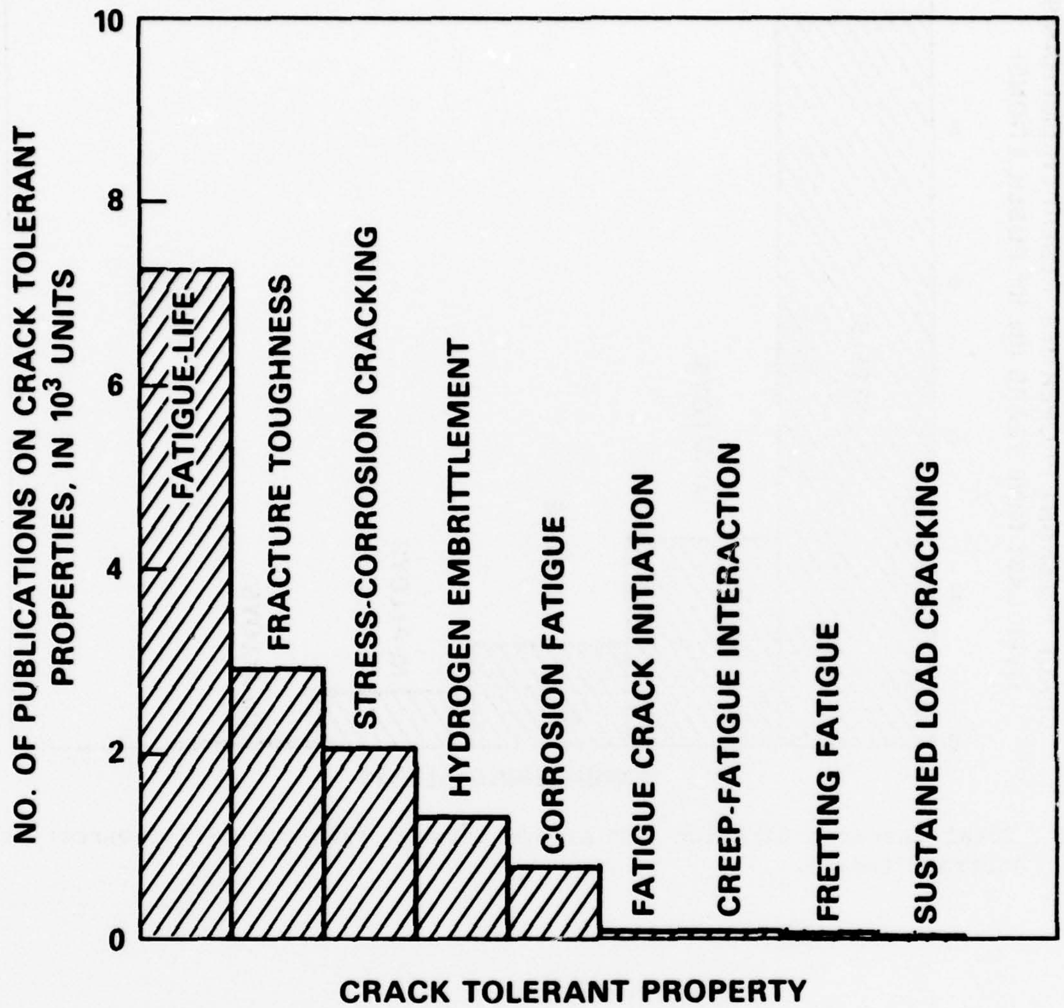

Fig. 9 Total Research Citation for Various Crack Tolerant Properties between 1966 and 1977 (Source: Metal Abstract Index).

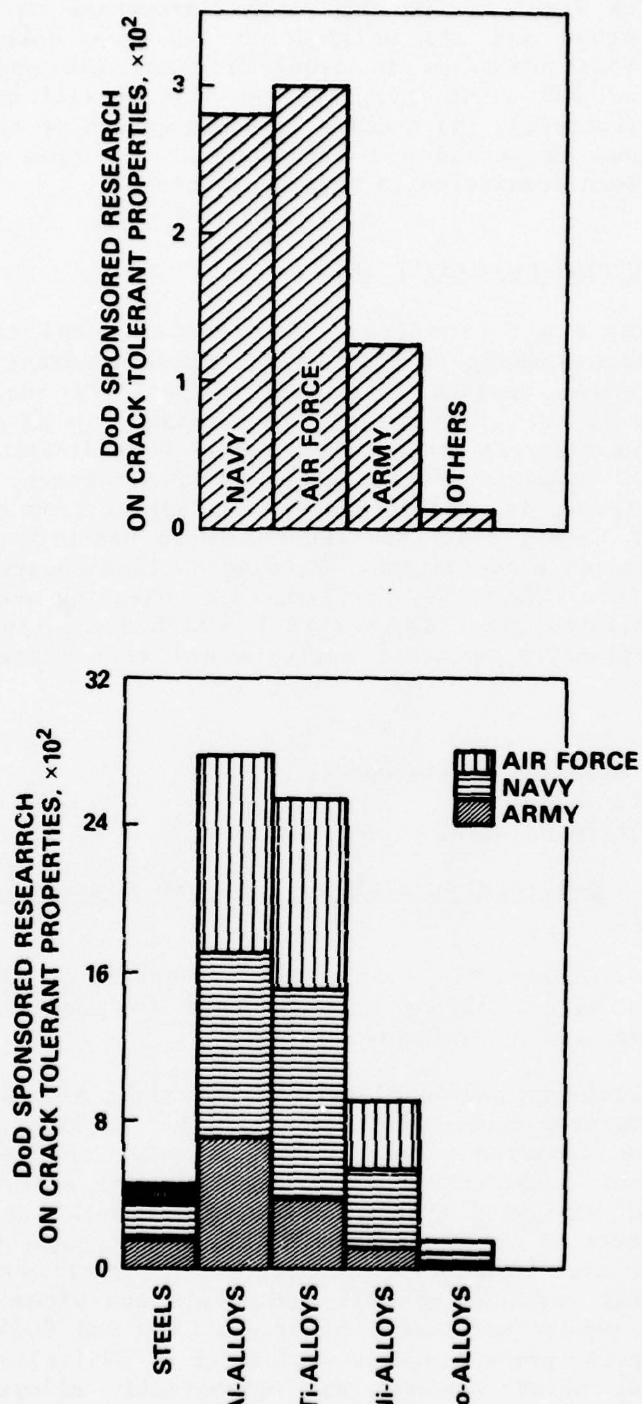

Fig. 10 Current Distribution of DoD work in Crack Tolerant Properties (Source: DD Forms 1498).

with steels nickel alloys not very far behind (240 citations dealing with Ni-alloys and 210 citations on steels). Of the various processes on surface protection, vapor deposition method and its utilization has been investigated the most. Presenting the various processes in order of their R&D popularity, they are: (1) vapor deposition (689 citations), (2) ion-plating (141 citations), (3) ion-implantation (131 citations), (4) coating by rapid quench of surfaces (47 citations) and (5) laser processing method (33 citations). The more traditional coating processes have not been considered in this evaluation.

IV. SYNOPSIS OF CURRENT R&D ACTIVITIES

Because of the short time frame allowed for completing this survey on current R&D activities seeking to improve the crack tolerant properties of high strength alloys, it was decided that a direct mailing request would be most effective in obtaining this information. Accordingly, a single page format was devised for reporting relevent projects and copies were distributed to key members of the materials R&D community in the Army, Navy, Air Force, DARPA, and NASA as well as IR&D participants in private industry. Judging from the response to this inquiry, it is fair to say that this general topic has wide-spread interest and support in the contacted organization. Because of time constraints, the synopsis of inputs received from this survey are limited to on-going activities and reports which have been published after January 1978. Also note, the inputs received on related topics of fracture mechanic analysis and test procedure were omitted.

ARMY INPUTS

1. US Army Research & Development
   Dover, NJ 67801
   (Dr. Jeffrey Waldman)

1.1 TITLE: Development of High Strength Homogeneous Aluminum Alloy Materials

Technical Objective: Improve the properties of high strength wrought aluminum alloys through improvements in processing techniques and development of new alloys.

Recent Progress and/or Plans: Light weight aluminum materials exhibiting improved combinations of strength, ductility, fracture toughness, corrosion resistance and fatigue behavior are desirable. Thermal-mechanical treatments (ITMT and FTMT) and alloy development offer means of achieving such goals. Current work involves investigating the effects of various thermal-mechanical treatments such as ITMT and FTMT on the engineering properties of ingot metallurgy and powder metallurgy versions of CT91 alloy with and without Co, Cr, or Zr as well as powder metallurgy materials CT90 and 7075 alloy. Work will begin on the processing and evaluation of CT91 alloy produced from air atomized, splat quenched and mechanically alloyed materials. The alloy development work will involve completing the thermomechanical processing of the powder metallurgy aluminum alloys containing Li. Work is also being carried out on superplastic forming of high strength aluminum alloys.

References:

DD Form 1498 is available from DDC under agency accession number DA OB 0453.

1.2 TITLE: Corrosion Fatigue Behavior of Aluminum Alloys

Technical Objective: The objective of the work is to investigate the corrosion fatigue behavior of both 7000 series powder metallurgy and ingot metallurgy aluminum alloys in both inert and aggressive environments. The fatigue behavior will be determined by measurements of the fatigue crack growth rate at high ΔK values.

Recent Progress and/or Plans: The fatigue crack growth rate will be measured at various high ΔK values for 7075-T6 and a new aluminum powder metallurgy alloy MA87. The variables to be examined are the environment, frequency, wave form, and stress intensity ratios. The influence of these variables will be described in terms of fracture mechanics parameters.

References:

DD Form 1498 is available from DDC under agency accession number DA OB 0677.

1.3 TITLE: Precision Forged Aluminum Powder Metallurgy Helicopter Components

Technical Objective: This project is a joint program with the Air Force Materials Laboratory in which the manufacturing technology will be established to produce aluminum alloy powder metallurgy structural airframe (Air Force) and helicopter (Army) precision forged components. The goals of the program are to produce parts which are lower cost than conventional ingot metallurgy forgings, and are superior in mechanical properties, stress corrosion resistance and fatigue performance.

Recent Progress and/or Plans: The program will be carried out as a 3 Phase cooperative Army-Air Force MM&T project. Phase I will be a 12 month effort in which the powder producer/forger will establish the precision forging practice involving such things as powder production, design/build vacuum forging facility, compaction evaluation, subscale perform design/forging trials. Phase II will be a 12 month effort by the powder producer/forger involving scale up and production forging of selected air-frame and structural parts. Phase III will be a 9 month effort by the airframe and helicopter manufacturers involving structural verification testing including full scale static and fatigue testing as well as complete economic evaluation.

References:

Technical reports of this project will be published.

1.4 TITLE: Microstructure/Processing Control for Aluminum P/M Wrought Products

Technical Objective: The overall objective of this project is to investigate the interrelationship of process variables on the structure and properties of high strength aluminum P/M wrought products.

Recent Progress and/or Plans: The project involves developing (1) an understanding of the interrelationship of the product fabricating variable of temperature-compensated strain rate and microstructure in high strength aluminum P/M wrought CT90 and CT91 products from billets produced with production-scale thermal practices and (2) an understanding of the inter-relationship of the microstructure and strength in high strength aluminum P/M wrought CT90 and CT91 products, to achieve improved properties. Based on the above work, these property improvements will be demonstrated in extrusions of CT90 and CT91 alloys produced from 3,300 lb. billets.

References:

DD Form 1498 is available from DDC under agency accession number DA OB 0679.

1.5 TITLE: Advanced Processing of Magnesium Alloys

Technical Objective: The overall objective is to improve the formability and toughness of magnesium alloys through the use of advanced processing techniques.

Recent Progress and/or Plans: Work is directed initially towards investigating the superplastic forming of magnesium alloys. This work will involve documenting those parameters necessary to achieve superplastic flow. The parameters to be investigated are grain size, deformation temperature and strain rates. Selected commercial alloys will be evaluated. The grain size will be tested at different temperatures and strain rates. Subsequent work will involve investigating the application of powder metallurgy techniques to magnesium alloys.

References:

DD Form 1498 is available from DDC under agency accession number DA OB 0678.

ARMY INPUTS

1A. Army Materials and Mechanics Research Center
Watertown, MA 02172
(Dr. E. B. Kula)

1A.1 TITLE: Structure & Deformation Characteristics of Rheocast Metal

Technical Objective: Develop specific wear resistant composites of aluminum base alloys and the techniques and procedures for their production using rheocast and/or associated processes.

Recent Progress and/or Plans: Composites of wrought and cast aluminum base alloy, containing particulate additions of non-metals and the aluminum alloy matrices will be studied and related to process variables during composite preparation. Net shape forming and hot working characteristics of the composites will be studied using thixoforging and hot extrusion techniques. The wear, tensile and fatigue properties of the composites will be determined and related to interface interactions, composite compositions, composite structures (size, amount and distribution of the non-metals) preparation and forming operations.

References:

"Structure and Deformation Characteristics of Rheocast Metals," AMMRC-CTR 79-2, January 1979, Contract No. DAAG46-76-V-0046.

DD Form 1498 is available from DDC under agency accession number DAOG 4805.

1A.2 TITLE: Interrelationship of Sulfur and Phosphorous Effects on Toughness of Steels

Technical Objective: Evaluate the effects of phosphorus and sulfur in steels, to determine whether the two elements can be considered as having a cumulative effect, and if so, to determine the nature of these effects. These relations could be utilized in the manufacturing of steel, the selection of steels, and in updating specifications.

Recent Progress and/or Plans: Two phases are recognized in this investigation. Phase 1 is recommended for assembling and analyzing available data on the effects of phosphorous and sulfur. This survey would involve other variables, such as section size, heat treatment, composition, etc. It would encompass data from drop-weight tests (NDTT), fracture toughness measurements (K_{IC}), dynamic tear tests, as well as Charpy impact tests. A second phase would be generating data based upon the results of the Phase 1 study. At this time an experimental program is visualized for Phase 2, which involves deliberate variations of phosphorous and sulfur giving consideration to the strength level and grades of the low alloy steels. Results from this program should provide a means of enhancing armor for combat vehicle protection.

References:

DD Form 1498 is available from DDC under agency accession number DAOG.

1A.3 TITLE: Fracture Behavior Evaluations of High Performance Helicopter Gear Materials

Technical Objective: The objective of this program is to optimize the fracture resistance properties of high temperature gear steels both at elevated temperature and at room temperature after having been exposed to elevated temperatures for extended periods.

Recent Progress and/or Plans: The Army is currently evaluating several tool steels for high performance gear applications. A major problem is the fracture toughness of these candidate steels after exposure to elevated temperature. The above program focuses on the fracture resistance of these alloys and the development of a new alloy composition based on the properties and compositions of the candidate alloys.

References:

"Heat Treatment, Structure, and Properties of Standard and Modified Vasco X-2 Carburizing Grade Gear Steels," Fopiano, P.J., and Kula, E.B., ASME Design Engineering Technical Conference, Chicago, IL, Sept. 1977.

"High-Cycle and Impact Fatigue Behavior of Carburized Steels," Diesburg, D.E., SAE Publication 780771, September 1978.

DD Form 1498 is available from DDC under agency accession number DAOG-4773.

1A.4 TITLE: Inclusion in Electroslag Remelted Ingots

Technical Objective: Investigate the morphology and effects of inclusions in high strength steel produced by ESR processing. The goal is to determine those conditions during thermal processing when the inclusions form, ripen, or dissolve and to relate those conditions to changes in the size distribution of inclusions. Explanations are to be sought for the reduction in ductility and toughness, particularly in the through-thickness direction, often observed in low-sulfur ESR processed steels.

Recent Progress and/or Plans: Samples of AISI 4340 ESR ingots were heated to various temperatures in the overheating range and then examined with the scanning transmission electron microscope. Inclusion types and their morphology have been identified in a commercial steel as predominately manganese sulfides and aluminum nitrides. A computer model has been developed which compares the size distribution of sulfides measured in a 4340 steel reported in the open literature. Similar experiments are to be performed on steels treated with rare earth additions and on steels heated to the ferrite-plus-austenite range.

References:

DD Form 1498 is available from DDC under agency accession number DAOG-4802.

1A.5 TITLE: Feasibility Study of Nuclear Magnetic Resonance for Ion Implanted Layers in Metals

Technical Objective: To make test measurements to determine whether Nuclear Magnetic Resonance is sensitive enough to provide information about the immediate atomic environments about ions which have been implanted in metals. Such information would be important to understanding the novel alloys that can be created by ion implantation.

Recent Progress and/or Plans: This program has just begun. The signal-to-noise-ratio expected for NMR in metal single crystals and in solid polycrystalline materials is being investigated, first, by intensive review of the literature. This is a nonstandard problem because the NMR is conducted only near the surface of a solid metal piece, owing to the existence of the RF skin depth. Test measurements on metal rods will be made, and also measurements on alloy rods. These will be evaluated to determine whether the unique kinds of information NMR can in principle get, can in practice be obtained from ion-implanted layers.

References:

DD Form 1498 is available from DDC under agency accession number DAOG-4817. The potential of the NMR technique for understanding the microstructure of alloys is illustrated by the following recent publication by the investigators: Paul L. Sagalyn and Michael N. Alexander, Physical Review, Vol. B15, pp. 5581-5597, 15 June 1977, "Electric-field-gradient tensor in nonmagnetic dilute alloys of copper."

1A.6 TITLE: Hot Isostatic Pressing of Titanium Powders

Technical Objective: Consolidation of aircraft quality powder shapes and pre-forms by hot isostatic pressing (HIP) presently requires use of costly gas-tight containers which are expended in process. Partly because of container expense, HIP parts are commonly limited to simple shapes, e.g., discs and cylinders. The objective of this research is development of a HIP method for consolidation of metal powders to obtain irregular shapes, employing reusable molds and obviating the need for expendable containers. Consolidation of titanium alloy compacts will be undertaken with intent of demonstrating materials suitable for application in drive systems of helicopters replacing forged or cast parts.

Recent Progress and/or Plans: The approach will investigate partial consolidation of loosely compacted powder metal preforms by formation (or infiltration with) a transient-liquid-phase which, interacting with the basic powder, forms a higher melting product and solidifies,

leaving at least an impervious skin. The partially consolidated item will then be removed from its mold and transferred to a HIP unit for further compaction and hologenization, without further encapsulation. Properties of titanium alloy compacts consolidated by this process will be determined and reported.

References:

DD Form 1498 is available from DDC under agency accession number DAOG-4760.

1A.7 TITLE: Surface Sealing of Powder Metal Compacts for Hot Isostatic Pressing

Technical Objective: The objective is to simplify the application of hot isostatic pressing to metal powders. This simplification is to be achieved by heating the surface of a porous metal compact to a sufficient depth to obtain a gas-tight skin. Several methods of heating will be investigated, noting the need to avoid atmospheric contamination. Proposed heat sources will include laser, electron beam, and high-frequency electromagnetic field. The effectiveness of surface sealing will be ultimately determined on the basis of densification in hot isostatic pressing.

References:

DD Form 1498 is available from DDC under agency accession number DAOG-4809.

1A.8 TITLE: Cast Titanium Compressor Impellers

Technical Objectives: To develop and demonstrate an investment cast plus HIP Process for the fabrication of titanium centrifugal compressor impellers. AMMRC will provide technical support for the program to USAR&L-AVRADCOM.

Recent Progress and/or Plans: Two 3 year contracts were recently signed with Solar Turbines International and Detroit Diesel allism. The program is to be conducted in four phases. Briefly stated; (1) establishment of common technology and evaluation of alternate, advanced alloys. (2) Pilot production and evaluation of final impellers in the selected alloys. (3) Assurance testing of the impellers by spin aerodynamic and vibration engine and rig tests. (4) Economic analysis of the cast product as it affects overall life cycle cost of the impeller.

References:

Bimonthly Letter Progress Reports (DAAK51-78-C-0020 and DAAK51-78-C-0019). DD Form 1498 is available from DDC under agency accession number DAOG-4685.

NAVY INPUTS

2. David W. Taylor Naval Ship Research and Development Center
Annapolis Laboratory
Annapolis, MD 20084
(Mr. R.J. Wolf)

2.1 TITLE: Low Yield Strength Welds

Technical Objective: Assess and extend technology related to the effective and reliable utilization of ferritic and austenitic weld metals having a yield strength less than the conjoint base metal.

Recent Progress and/or Plans: Strength undermatched weldments have been produced in HY-100 steel using ferritic (Linde 65) and austenitic (Nitronic 50W) weld filler metals. Welding joint designs being investigated include single and double vee and narrow gap configurations. Evaluation is under way of weld metal mechanical properties and microstructure, and weldment explosion bulge and fatigue test performance.

References: None to date.

2.2 TITLE: Subcritical Cracking of High Strength Steel Weldments

Technical Objective: Develop the metallurgical and fabrication technology guidelines to provide steel weldment systems (100-200 ksi YS) which will be resistant to subcritical cracking (SCC) in seawater. This includes stress corrosion and hydrogen stress cracking.

Recent Progress and/or Plans: Results of 500 hour laboratory verification tests on HY-130 welds prepared using fine bead practice have indicated that composition can have a significant effect on weld metal K_{ISCC}, zinc coupled. The fine bead GTAW weld prepared using an HY-130 base plate chemistry showed substantially higher K_{ISCC} values than welds prepared using standard filler wire chemistries. Additional verification tests are being performed to establish levels of improvement with existing metals. Work on the 10Ni-HY-180 steel in seawater and gaseous H_2S environments indicates that at equivalent strength levels, the 10Ni alloy offers no advantage in K_{ISCC} compared to standard HY-130 steel. Evidence of longer failure times for the overaged material compared to HY-130 base plate was suggested from cantilever beam tests. Microstructural analyses of weld metals indicate that refined weld metal structures contain retained austenite which may reduce hydrogen diffusivity and reduce SCC growth rates. A critical assessment of the available SCC data base was performed and areas for investigation were identified. Analyses of base line study results are in progress.

References:

Holsberg, P.W. and E.C. Dunn - "High Strength Steel Weldment Subcritical Cracking Program - Preparation and Characterization of Baseline Materials" - DTNSRDC Report MAT 77-95, February 1978.

Fujii et al - "SCC Characterization of High Strength Steels - Base Metals and Weldments" - NRL Report 8230, May 1978.

Hauser, D. et al - "High Strength Steel Weldment Subcritical Cracking Program - Review of Sub-Critical Cracking in Steel Weldments" - BATTELLE Columbus Laboratories Contract - DTNSRDC Report SME 78-89.

2.3 TITLE: Fabrication Procedures for Inconel 625 Clad HY-130 Steel

Technical Objective: Develop improved fabrication processes and advanced materials to maximize design performance, increase reliability and operational life and reduce associated life cycle cost of high performance ships. Specifically, develop basic fabrication procedures for Inconel 625 clad HY-130 steel.

Recent Progress and/or Plans: Microprobe evaluation of bead-on-plate Inconel 625 on HY-130 steel welds has been completed, basic weld joint geometry and welding procedures have been determined, welds have been fabricated for mechanical property and metallographic analysis, evaluation of full alloy welds is complete.

References:

Morris, R.A. - "Development of Inconel 625 Clad HY-130 Steel Plate", DTNSRDC Report MAT-77-101, September 1978.

2.4 TITLE: Alforge Panels

Technical Objective: Develop and characterize the Alforge Process for for joining 5456 alloy aluminum. Determine properties and performance of Alforge panel weldments.

Recent Progress and/or Plans: Fabrication and accelerated corrosion testing of modified Alforge process weldments for screening purposes has been completed. Alforge modifications examined included: (1) preweld thermal and stretching treatments, (2) welding heating and joining cycles, (3) post weld thermal and peening treatments. Based on results of screening tests process modifications have been selected and used in joining panels for corrosion and mechanical properties tests.

References: None to date.

2.5 TITLE: Weld Bonding

Technical Objective: Evaluate use of adhesive bonding with resistance spot welding and stud welding for joining primary load-bearing structures.

Recent Progress and/or Plans: Weld bonded, stud bonded and adhesive bonded lap joints fabricated by Rohr Industries were tensile shear tested. Adhesive bonded joints exhibited highest shear strength while weld bonded joints exhibited lowest shear strength. Krouse axial

fatigue specimens were machined from weld bonded, stud bonded and adhesive bonded panels and are now under test. Panels exposed for one year in seawater splash and spray atmosphere have shown no visible degradation at the adhesive joint. Joint design studies were initiated using simple lap, double strap, tapered double strap and single strap reinforced butt weld configurations. The joints are being tensile shear tested.

References: None to date.

3. Naval Air Development Center
Warminister, PA 18974
(Mr. F.S. Williams)

3.1 TITLE: Research on Catastrophic Corrosion Damage Phenomena and Damage Control in Naval Aircraft

Technical Objective: To develop advanced materials science concepts for fracture and corrosion control. To study environmental embrittlement phenomena of high strength steel, Ti and Al alloys. Using an integrated mechanistic approach develop the means for mitigation of cracking of high strength aircraft alloys.

Recent Progress and/or Plans: A research study on crack arrestment of high strength 4340 steel (Ftu = 260 ksi) in the environment containing high humidity and chloride has been completed and an effective fatigue crack growth retardation has been achieved. In addition, preliminary experiments have been made using a physical constraint, magnetic field, and it was observed that absorption of hydrogen in steel was lower when magnetic field was imposed on the system. Further studies are being made to confirm this observation.

References:

V.S. Agarwala and J.J. DeLuccia - "New Inhibitors for Crack Arrestment in Corrosion Fatigue of High Strength Steels."

4. Naval Air Systems Command
Washington, DC 20361
(Dr. R. Schmidt)

4.1 TITLE: Titanium 6Al-4V Fatigue Resistance Improvement

Technical Objective: Initially this program will assess the potential of solution treating and quenching on various product forms of Ti-6Al-4V as a means of enhancing fatigue life of critical structural components under realistic aircraft fatigue loading conditions. Later, a demonstration of a specific improved processing method will be made on a typical aircraft part.

Recent Progress and/or Plans: (New Program) Work to date performed at the George Washington University indicates a ten-fold improvement in the fatigue life of Ti-6Al-4V in laboratory specimen form. These

specimens have been solution treated and water quenched. This is a considerable interest since titanium alloys affording significantly improved crack initiation resistance and longer fatigue life would lead to more efficient structural components.

References: None to date.

4.2 TITLE: Aluminum Powder Metallurgy Extrusions

Technical Objective: To determine properties of small MA-87 aluminum powder metallurgy extrusions in an exfoliation resistant, T-7651 type temper, thus providing data for use in designing parts for prototype structural hardware.

Recent Progress and/or Plans: Four lots of MA-87 extrusions will be produced in two shapes. Extrusions will be produced under mill conditions and heat treated to maximum strengh commensurate with adequate exfoliation corrosion resistance. The test program will consist of tension, compression, shear and bearing strength, tension and compression elastic modulus, exfoliation corrosion, stress corrosion cracking, notched axial fatigue, spectrum fatigue, fatigue crack growth and fracture toughness. Properties of PM will be compared with 7075 and 7050 ingot metallurgy alloys.

References: None to date.

4.3 TITLE: Fracture in High Strength Thin Sheet Laminates

Technical Objective: To improve fracture behavior of critical aircraft parts.

Recent Progress and/or Plans: Al/Al laminate systems were evaluated, showing substantially higher fracture toughness in the crack divider orientation than corresponding monolithic plate alloys. Fracture toughness improvement through lamination ranged from 33% to 56%. The crack divider fracture toughness of a laminate was shown to depend ultimately on the plane stress toughness of the individual primary metal layers comprising the laminates. The key factor controlling plane stress failure of the primary layers is that failure occurs at the primary/secondary bond prior to a plane strain condition through the thickness of the laminate. In metal/metal laminates, this means that the interleaf metal strength must be less than the primary metal strength, thus preventing excessive delamination. Laminates of 7475/1100 Al had a fracture toughness (K_c) 63% higher than those of 7075/7072 Al.

References: None to date.

5. Naval Research Laboratory
Washington, DC 20375

5.1 TITLE: Novel Processes

Technical Objective: The objective of this program is to place this microcrystalline or alloyed rapidly solidified layers on structural alloys in order to eliminate deleterious surface effects. Such layers could increase the corrosion resistance of the alloys, enhance their fatigue characteristics or eliminate/control other surface limited properties.

Recent Progress and/or Plans: Potentiostatic polarization measurements of Al surfaces continue. Surface metals on Ti and 304 stainless have produced no flaws. Alloying studies and microprobe analysis of low carbon steels has begun. Procedures for studying fatigue and wear are under analysis.

References:

Characteristics of Laser Surface Melted Al Alloys - Applied Optics, Vol. 17, #6, 1978.

Porosity Formation in Laser Surface Melted Al Alloys - Scripta, Metall. Vol 12, p. 57-60, 1978.

DD Form 1498 is available from DDC under agency accession number DN780030.

5.2 TITLE: Welding Metallurgy

Technical Objective: Correlations between properties and structures have been well developed for base metals but are tenuous for weldments. The objective of this task is to correlate the mechanical properties of weldments, especially weld metal and heat affected zone properties, with their structures, i.e., micro- and macro-structures. Such knowledge and data would then serve as a guide in the improvement of existing naval weldments and in the development of future naval weldment systems.

Recent Progress and/or Plans: The fracture resistance of 0.5 in. thick laser welds of HY-80, HY-130, Al 5456 and Ti 621/0.8 alloys have been measured by dynamic tear (DT) tests. The titanium and HY-130 alloys exhibited extremely good DT values (near base metal properties). Al 5456 had DT values similar to these gas metal arc welds whereas the HY-80 DT values were low.

References:

J. Stoop and E.A. Metzbower, "A Metallurgical Characterization and Assessment of SMA, GMA, EB, and LB Welds of HY-130 Steel," NRL Formal Report 8157, Sept 1977.

DD Form 1498 is available from DDC under agency accession number DN780-032.

5.3 TITLE: Laser Application of Coatings

Technical Objective: Develop new techniques in which high energy lasers are used to apply wear or corrosion resistant coatings to structural alloys. Coatings are applied by the process of laser spraying, in which powder is injected into the laser beam and propelled onto an alloy substrate for surface melting and consolidation. Coatings are also applied by plasma spraying in combination with subsequent remelting by the laser. The applied coatings are tested to evaluate the enhancement of surface-related properties as a function of chemical composition and laser-processing parameters.

Recent Progress and/or Plans: The dynamics of particle propulsion by laser beams in responses of laser-irradiated substrate. This information is used to adjust the laser beam parameters to give the best adhesion of powder particles to the substrate, and to give the desired microstructures in the resulting coatings. Coatings are evaluated optical and electron microscopy and by wear and corrosion tests.

References:

Laser Remelt Consolidation of Plasma-Sprayed Titanium, by J.D. Ayers and R.J. Schaefer, Report of NRL Progress, May 1979, p.8.

Consolidation of Plasma-Sprayed Coatings by Laser Remelting, by J.D. Ayers and R.J. Schaefer, Proceedings of S.P.I.E. Symposium on Laser Applications in Materials Processing, San Diego, California, August 27-28, 1979.

5.4 TITLE: Laser Processing of Materials

Technical Objective: The objective of this program is to produce unique materials by means of the special heating capabilities of high energy lasers. These materials can take many forms, including corrosion protective coatings, fibers for high strength reinforced composites, and high purity powders of reactive metals. This program will produce these materials by a variety of laser reactive methods, and will characterize their microstructures and their mechanical and chemical properties. The laser processing parameters will be varied to produce the optimum properties for potential applications in Navy systems.

Recent Progress and/or Plans: (1) Established Crystalline nature of laser melted titanium alloys with extreme cooling rates. (2) Analyzed thermal response of substrates subjected to rastered laser heating. (3) Selected Systems for plasma spray-laser remelt experiments to produce wear and corrosion resistance.

References:

Motion of Al_2O_3 Particles in High Energy Laser Beams by R.J. Schaefer, T.R. Tucker and J.D. Ayers, Report of NRL Progress, April 1979, p. 17.

Propulsion of Powders by Laser Beams in Vacuum, by R.J. Schaefer, T.R. Tucker and J.D. Ayers, Report of NRL Progrss, January 1979, p. 16.

Propulsion of Powders by High Energy Laser Beams, by R.J. Schaefer, T.R. Tucker, and J.D. Ayers, in Proceedings of ASM Conference on Applications of Lasers in Materials Processing, April 1979.

5.5 TITLE: Crack Initiation and Growth Characteristics of Ti-8Al-1Mo-IV

Technical Objective: Develop methods for improvement of crack initiation and crack growth resistance in Ti-8Al-1Mo-IV as a function of heat treatment. Establish rational micromechanistic interpretation of results.

Recent Progress and/or Plans: An approximate doubling of stress-corrosion-cracking resistance (K sub Iscc) has been achieved in Ti-8Al-1Mo-IV by microstructural modifications obtained through heat treatment. Improvements are obtained by changing the microstructure from that associated with the presently used duplex-annealed condition to Widmanstatten types resulting from various beta-anneal heat treatments.

References:

G.R. Yoder, L.A. Cooley and T.W. Crooker, "On Improvement of Environmental Crack Propagation Resistance in Ti-8Al-1Mo-IV Through Microstructural Modification," NRL Progress Report to NAVAIR 6384-68N:GRY:svs of 26 October 1977.

G.R. Yoder, L.A. Cooley and T.W. Crooker, "Enhancement of Fatigue Crack Propagation Resistance in Ti-8Al-1Mo-IV Through Microstructural Modification," Report of NRL Progress, December 1977, pp. 10-11.

G.R. Yoder, L.A. Cooley and T.W. Crooker, "Enhancement of Stress Corrosion Cracking Resistance in Ti-8Al-1Mo-IV Through Microstructural Modification," Report of NRL Progress, March 1978, pp. 12-14.

G.R. Yoder, L.A. Cooley and T.W. Crooker, "Quantitative Analysis of Microstructural Effects on Fatigue Crack Growth in Widmanstatten Ti-6Al-4V and Ti-8Al-1Mo-IV," NRL Report (pending).

G.R. Yoder, L.A. Cooley and T.W. Crooker, "Rationale for Enhanced Resistance to Fatigue Crack Growth in Beta-Annealed Ti-8Al-1Mo-IV," Report of NRL Progress (pending).

DD Form 1498 is available from DDC under agency accession number DN68039.

5.6 TITLE: Research on Crack Initiation and Growth in High-Strength Metals

Technical Objective: A quantitative understanding of the crack growth and fracture resistance characteristics of high-strength alloys is necessary for failure-safe design of high-performance naval structures. The objective is to determine metallurgical principles for optimization of crack growth and fracture resistance and to translate crack growth resistance principles to actual service conditions, including spectrum loading and the marine environment.

Recent Progress and/or Plans: Further studies on the role of the Widmanstatten packet size in controlling fatigue-crack growth resistance of alpha + beta titanium alloys have been completed. Previously developed relationships between microstructural features and crack growth resistance have been validated over a much broader range of microstructures. Preliminary studies on the influence of metallurgical factors on stress-corrosion-cracking resistance in titanium alloys have been completed.

References:

G.R. Yoder, L.A. Cooley and T.W. Crooker, "Enhancement of Fatigue Crack Growth and Fracture Resistance in Ti-6Al-4V and Ti-6Al-6V-2Sn Through Microstructure Modification," ASME Transactions, Journal of Engineering Materials and Technology Vol. 99, Series H, No. 4, October 1977, pp.313-318.

G.R. Yoder, L.A. Cooley, and T.W. Crooker, "Fatigue Crack Propagation Resistance of Beta-Annealed Ti-6Al-4V Alloys of Differing Interstitial Oxygen Contents," Metallurgical Transactions (pending); also, NRL Report 8166, October 4, 1977.

T.W. Crooker, "Subcritical Crack Growth in High-Strength Alloys," Proceedings of the ONR International Symposium on Fracture Mechanics, George Washington University, Washington, DC., September 11-13, 1978 (pending).

DD Form 1498 is available from DDC under agency accession number DN020105.

5.7 TITLE: Initiation of Cracks in Low-Cycle Fatigue of Titanium Alloys

Technical Objective: Determine the relationship between low-cycle fatigue crack initiation resistance and fatigue crack propagation resistance for select microstructural modifications, so that a fundamental basis for metallurgical optimization of total fatigue life can be established. Established rational micromechanistic interpretation of results.

Recent Progress and/or Plans: New Problem. Systematically determine the low-cycle fatigue crack initiation resistance of Ti-6Al-4V for microstructural modifications which are already well characterized in terms of fatigue crack propagation resistance, mechanical properties and quantitative metallographic parameters. The different microstructures, as affected by changes in heat treatment and interstitial oxygen content, are to be examined for crack initiation resistance under conditions of constant stress amplitude.

References: None to date.

5.8 TITLE: Defect and Structure Analysis of Materials

Technical Objective: Establish the capability of small-angle neutron scattering (SANS) for the determination of prefracture structural changes in highly stressed materials and for the determination of the mechanism and kinetics of void and second phase nucleation and growth in naval alloys used at elevated temperatures. Correlate these results with those from other non-destructive evaluation methods.

Recent Progress and/or Plans: Preliminary studies have shown that SANS may be used to observe the scattering of voids resulting from vacancy condensation. In Nichrome V rods, subjected to creep at 810°C under stresses 29 to 41 MPa, the dependence of void density with decreasing stress is clearly observed. In another application, crystallization behavior of amorphous metals was studied by SANS. A significantly higher scattering profile was obtained for the crystallized alloy compared to the amorphous state, the difference being relatable to the crystalline interface density.

References:

"Nondestructive Determination of Texture and Microscopic Defects by Means of Neutron Scattering Techniques," C.S. Choi, H.J. Prask, S.F. Trevino, H.A. Alperin, M. Fatemi and B.B. Rath, the Proceedings of the 27th Defense Conference on Nondestructive Testing, October 23-26.

5.9 TITLE: Ion Implantation of Materials

Technical Objective: Systematically investigate ion implantation method for the beneficial modification of surface-sensitive and life-limiting properties of metals and alloys with particular emphasis given to properties such as resistance to wear, fatigue and corrosion. Characterize microstructure and profile of surface chemistry to quantitatively evaluate the effect on the alloy properties.

Recent Progress and/or Plans: Recent investigation has shown that ion implantation can produce a graded alloy from the surface to the unchanged underlying bulk so that both can be independently optimized. The sliding wear rates between various steels were significantly

reduced by implantation of nitrogen, carbon and titanium. Fatigue life-times in low-carbon steels and Ti-6Al-4V alloys has been increased anywhere from 5 to 100 times by ion implantation. It has now been established that implantation of relatively small amounts of properly selected atoms into the surface layers of an alloy brings about striking changes in its corrosion behavior.

References:

"Improvement of Metal Properties by Ion Implantation," J.K. Hirvonen, C.A. Carosella, R.A. Kant, I. Singer, R. Vardiman, and B.B. Rath, Thin Solid Films, 63 (1979).

J.K. Hirvonen, J.W. Butler, T.P. Smith, R.A. Kant and V.C. Westcott, Radiat. Eff., to be published.

R.G. Vardiman, R.A. Kant, T.W. Crooker, and B.B. Rath, to be published.

"Surface Hardening of Beryllium by Ion Implantation," R.A. Kant, J.K. Hirvonen, A.R. Knudson, and J.S. Wollam, Thin Solid Films, 63 (1979).

"Application of Ion Implantation for the Improvement of Localized Corrosion Resistance of M50 Bearing Steel," Y.F. Wang, C.R. Clayton, G.K. Hubler, W.H. Lucke, and J.K. Hirvonen, presented at the International Conference on Metallurgical Coating, April 23-27, 1979, San Diego, California.

6. Office of Naval Research
Arlington, VA 22217
(Dr. B.A. MacDonald)

6.1 TITLE: Materials Support Technology: High Toughness Cryogenic Steels

Technical Objective: This research is directed towards improving steels contemplated for use in Navy superconducting machinery. The principle aim will be to develop adequate criteria for obtaining high toughness with high yield strength in ferritic steels.

Recent Progress and/or Plans: A substantial decrease in the ductile-brittle transition temperature was observed for the Fe-8Ni-2Mn-0.25Ti alloy on introducing 3 to 5 percent austenite. Austenite induced a similar improvement in the cryogenic impact toughness of ferritic Fe-Mn alloys. It was observed that a 50 percent in crease in Charpy impact energy occurred above the ductile-brittle transition temperature due to the presence of retained austenite.

References:

J.W. Morris,Jr., S. Jin, and C.K. Syn, "Role of Retained Austenite on the Toughness of Cryogenic Steels with and without Carbon," Proc. Second International Conference on Mechanical Behavior of Materials, Boston, August 16-20, 1976, p.1159. TR#7 - Mechanical Stability of Retained Austenite in Tempered 9Ni Steel," by C.K. Syn, B. Fultz and J.W. Morris.

6.2 TITLE: Rare Earth Additions to Titanium Alloys

Technical Objective: Titanium alloys are important lightweight structural materials for use in aircraft and ships. Alloy microstructure and mechanical properties can be controlled by effective use of alloying and processing. This research will explore the effects of rare-earth additions to titanium alloys.

Recent Progress and/or Plans: Titanium ingots of Ti 6-4 with 0.1 wt. percent Er and 0.02 Y, 0.05 Y and 0.038 Y203 were cast, forged and beta processed or alpha-beta processed to plate form. Various annealing treatments were employed. The rare earth additives had no significant effect on ambient yield stress, fracture toughness or crystallographic texture from rolling. A sharper texture developed during annealing.

References:

TR#7 C.R. Whitsett, S.M.L. Sastry, J.E. O'Neal and R.J. Lederich, "Influence of Rare-Earth Additions of Properties of Titanium Alloys," July 1977.

6.3 TITLE: Metallurgical Structure and Properties of High Strength Alloys

Technical Objective: The researchers will explore the source of the high strength and toughness found in structural steels with the goal of improving these properties further. Structure of martensitic steels will be examined, as well as employing advanced powder metallurgy techniques to explore methods of producing high toughness, fatigue resistant steels of benefit to the Navy.

Recent Progress and/or Plans: Powders of 9Ni-4Co steel will be produced by rapid-solidification processing (RSP) and compacted to bulk specimens. The properties and structure of the RSP specimens will be measured and compared to conventionally processed material. A series of alloy steels of the Fe-Ni-Mo-Ti type will be used to determine the importance of volume change due to martensite formation to better understand steels toughened by strain-induced deformations. Research will be initiated on Fe-B type amorphous alloys to better characterize their glass forming tendencies.

References:

N. DeCristofaro, R. Kaplow and W.S. Owen, "The Kinetics of Carbon Clustering in Martensite," Met. Trans. A, 9A (1978), 821.

R.J. Salzbrenner, "Some Preliminary Studies on RSP 9Ni-4Co Steels," Rapid Solidification Processing, Claitor's Publishing, Baton Rouge (1978) 378 pgs.

6.4 TITLE: New Methcd for Fabrication of Turbine Disks

Technical Objective: Turbine disks are retired after logging a specified number of service hours because of the possibility of fatigue cracks. This research is aimed at developing a new method for fabricating disks with higher strength and improved fatigue life.

Recent Progress and/or Plans: The investigators will develop a technique for sequentially depositing thin liquid layers of metal alloys on a rotating mandrel. These layers will be rapidly solidified prior to the introduction of additional layers. High energy input in the form of a laser beam or electron beam will be required to assist the metal layer bonding. This method will be used to form a model turbine disk using an alloy based on the Ni-Al-Mo system, and the disk will be spin tested in vacuum at elevated temperature to determine the rupture strength.

References: None to date.

6.5 TITLE: Advanced Aluminum Alloys Based on Rapidly Solidified Powders

Technical Objective: This research addresses a possible method for producing high specific strength aluminum alloys for use in advanced Navy systems. Such alloys are needed for missile, aircraft and surface ship components where fatigue and/or creep are major design considerations.

Recent Progress and/or Plans: New Problem. The investigators will prepare rapidly-solidified powders by the roll quenching and ultra-sonic atomization techniques. The aluminum-lithium alloy system will be emphasized with controlled additions of Cd, Cr, Be and Mn Powders will be canned, extruded and then various heat treatments applied to optimize properties. Structure will be determined by transmission and scanning electron microscopy. Mechanical properties of interest to be measured include tensile properties, fatigue, toughness and creep rupture resistance.

References: None to date.

6.6 TITLE: Rapid Solidification Processing of Metal Alloy Surfaces

Technical Objective: The investigator will examine the potential of improving metal alloys by rapid solidification processing of their surfaces. Properties of interest to the Navy that might benefit from this processing include wear and corrosion resistance, fatigue resist-ance, and hardness.

Recent Progress and/or Plans: New Problem. Thin surface layers of selected steels will be laser or electron beam melted and rapidly solidified. Structural changes will be correlated with mechanical properties and processing variables. The steels to be processed include 4350, 440 C, M-2 tool steel and model alloy systems.

References: None to date.

6.7 TITLE: Effects of Residual Stresses on Microcrack Development

Technical Objective: The subject under investigation here relates to failure modes that can occur in materials used in naval jet engines. Fan blades and disks are routinely taken out of service due to possible fatigue microcrack formation. The proposed research will provide needed input towards solving this problem.

Recent Progress and/or Plans: New Problem. This research investigation will involve an examination of microcrack growth in the presence of surface residual stresses in titanium alloys. Effects of residual stress sign and magnitude will be found for growing microcracks. Crack opening displacement will be determined directly by scanning electron microscopy. Effective stress employed in the analysis of microcrack growth.

References: None to date.

6.8 TITLE: Hydrogen Embrittlement of High Strength Steels

Technical Objective: The objective of this research is to assess methods of reducing hydrogen embrittlement damage in high strength steels used in naval structures by control of surface properties.

Recent Progress and/or Plans: Studies of the effect of electrodeposited metals on the permeation of hydrogen through iron membranes were extended to Cd and Sn. Both metals strongly decreased hydrogen permeation when charging was carried out in 0.IN NaOH plus 2 ppm as solutions. At constant charging rate or at constant charging potential Sn was at least an order of magnitude more effective than Cd for comparable thicknesses. For a given charging current density the potential of the membrane shifted to more negative values in the order Fe Cd Sn indicating that the hydrogen evolution reaction is easier on iron than cadmium than tin.

References:

S.S. Chatterjee, B.G. Ateya and H.W. Pickering, TR #9, "Effect of Electrodeposited Metals on the Permeation of Hydrogen Through Iron Membranes," May 1978.

6.9 TITLE: Hydrogen Embrittlement of High Strength Steels

Technical Objective: The objective of this research is to assess methods of reducing hydrogen embrittlement damage in high strength steels used in naval structures by control of microstructure.

Recent Progress and/or Plans: It was shown that the addition of 3 percent Si to purified iron changed the crystallographic planes of hydrogen-induced cracks from the operating slip planes, (112), to the operating cleavage planes, (100). The transition from slip plane cracking to cleavage plane cracking occurs around 0.7 percent Se. The hydrogen crack induced surface morphologies of the Fe and Fe-Si alloys vary drastically. In pure Fe small planar segments and markings perpendicular to the direction of crack propagation are seen. In Fe-3Si alloys small periodic steps indicative of cleavage are seen. It is theorized that, at least in these ferritic materials, the hydrogen crack plane and mode of crack advance is a function of the intrinsic toughness of the ferrite lattice.

References:

TR #7 G.M. Pressouyre and I.M. Bernstein, "The Role of Trapping on Hydrogen Transport and Embrittlement," July 1977.

TR #8 F. Nakasato and I.M. Bernstein, "Crystallographic and Fractographic Studies of Hydrogen-Induced Cracking in Purified Iron and Iron-Silicon Alloys."

6.10 TITLE: Ion Implantation Metallurgy

Technical Objective: The objective of this research is to determine if the mechanical and chemical (corrosion) properties of naval alloys can be improved by ion implanting selected species in their surfaces.

Recent Progress and/or Plans: Studies of the effect of Ni ion implanted into a ferritic stainless steel have been carried out. Ni implants of 5 percent, 10 percent, 15 percent were made. Structural information about the implanted material was obtained by use of transmission electron microscopy (TEM) and replica methods; the latter gave information about sputtering damage. TEM analysis showed that no phase transformation had taken place even for the 15 percent alloy indicating the highly metasable nature of the alloys. Corrosion behavior, as indicated by electrochemical polarization tests, indicated improved corrosion resistance in acid solutions due to passive surface film modification.

References: None to date.

6.11 TITLE: Response of Ion Plated Metals Alloys to Cyclic Stress

Technical Objective: Many metallic components used in naval structures crack and fail under cyclic loading - fatigue. The object of this research is to determine the effect of ion plating and ion implantation on fatigue crack nucleation of metal substrates.

Recent Progresss and/or Plans: Coatings and substrate materials will be selected in order to separate the various parameters, e.g., crystal structure, stacking fault energy, shear modulus, misfit, residual stresses, etc., which control deformation behavior and fatigue crack initiation at the surface. Fatigue characterization will be based on strain controlled microscopy, transmission electron microscopy, replication techiques and interferometry will be used to elucidate the deformation mechanisms and associated fatigue crack initiation processes.

References: None to date.

6.12 TITLE: Rare Earth Modified High Strength Steels

Technical Objective: High strength steel components used by the Navy can be badly embrittled if they pick up hydrogen during processing or in service. Prior work has shown that rare earth additions to some high strength steels may be capable of reducing susceptibility to hydrogen embrittlement; this research is a further effort to assess pressing. Specimens will be heat treated to strength levels of about 200 KSI, charged with hydrogen from an electrolytic bath and tested for sustained-load delayed failure. Metallographic and fractographic analysis will be carried out.

References: None to date.

AIR FORCE INPUT

7. Air Force Materials Laboratory (AFSC)
Wright-Patterson Air Force Base, Ohio 45433
(Dr. Harris M. Berte)

7.1 TITLE: Improved High Temperature Fatigue Properties of Titanium Alloys By Noble Metal Ion Implantation/Plating

Technical Objective: To improve high temperature fatigue properties of Ti alloys by ion implantation/plating of noble metals which provide thermally and metallurgically stable coatings and inhibit the formation of Ti oxides and alpha (phase) casing.

Recent Progress and/or Plans: Current in-house efforts demonstrated that a very thin (1 micron or less) ion plated Pt coating improved the fatigue strength and creep resistance of Ti alloys simultaneously. A feasibility study of applying this technique to the 7th stage F-100 engine compressor blades is being conducted by Pratt & Whitney Aircraft and the preliminary results indicate that the fatigue strength of Pt coated airfoils increased by 30% compared with that of uncoated Bill-of-Materials blades.

References:

"Improved High Temperature Mechanical Properties of Ti Alloys by Pt Ion Plating," Shiro Fujishiro and Daniel Eylon, Thin Solid Films, 54 (1978) 309-315.

"Improved High Temperature Capability of Ti Alloys by Ion Implantation/ Plating," Shiro Fujishiro and Daniel Eylon, AFSC-TR-78 (to be published).

"Ion Plated Coatings on Ti Alloy," T.A. Eckler and B. A. Manty, Interim Report for F33615-78-C-5179, Jan. 1979.

7.2 TITLE: Metallurgical Factors Controlling Structure and Properties in High Strength Aluminum Powder Metallurgy Products

Technical Objective: To improve the reliability, particularly fatigue related properties, of high strength aluminum aerospace alloys by employing rapid solidification P/M approaches.

Recent Progress and/or Plans: Under Contracts F33615-74-C-5077 and F33615-77-C-5174 Alcoa has identified processing schemes that produce a wide variation in fatigue crack growth (FCG) behavior in high strength aluminum P/M alloys. In particular, residual stress-relief operations were shown to have a dramatic effect on FCG in the P/M alloys studied. Products that were not stress-relieved exhibited significantly slower FCG rates. Fatigue life was dramatically increased in all cases. Present program goals include mapping residual quenching stresses so that an accurate stress state in a test specimen can be determined analytically.

Although residual quenching stresses appear to have no adverse effect on crack initiation, future plans include examining processing effects on axial low cycle fatigue behavior as well as smooth and notched axial high cycle fatigue behavior.

References:

"Metallurgical Factors Controlling Structure in High Strength Aluminum P/M Products," AFML-TR-76-60, May 1976, AD 030 606.

8. Air Force Office of Scientific Research (AFSC)
Bolling Air Force Base
Washington, DC 20332
(Dr. Alan H. Rosenstein)

8.1 TITLE: Flow and Fracture Processes in Powder Metallurgical Nickel-Base Superalloys

Technical Objective: The objective of this research is to obtain insight into the factors and mechanisms that control the strength and stress-rupture properties of powder metallurgy nickel-base superalloy disks fabricated by hot isostatic pressing. As such, it will contribute to AF programs to exploit advanced cost-effective manufacturing methods (hot isostatic pressing of nickel alloy powders) for the production of critical engine components.

Recent Progress and/or Plans: Two basic mechanical properties of nickel-base superalloys fabricated by powder metallurgy techniques have been selected for study: stress rupture, and strength with emphasis on the yield stress. Several alloy compositions, including MERL-76, will be selected for detailed mechanical and microstructural characterization. Quantitative models will be constructed of the mechanical processes, and related to experimental observations.

References: None to date.

8.2 TITLE: The Effects of Small Deformation on Creep and Stress Rupture Behavior of ODS Superalloys

Technical Objective: The objective of this research is to determine mechanistically the effect of elevated temperature hot isostatic pressing (HIP), and compression or rolling treatments, on the creep and stress rupture behavior of ODS alloys. Microstructural changes induced by the pretreatment are expected to result in improvements in creep and stress rupture resistance of this class of alloys.

Recent Progress and/or Plans: Efforts will concentrate mainly on the gamma prime strengthened ODS superalloy MA-6000 and on the ODS solid solution (Ni-Cr) alloy MA-754. The possible effects of the presence of gamma prime precipitates during pretreatment will be assessed through HIP treatment above and below the gamma prime solvus of MA-6000.

8.3 TITLE: A Fundamental Study of the Processing of Oxide Dispersion Strengthened Metals

Technical Objective: The objective of this research is to determine the mechanical alloying and deformation processing factors that are most important in producing homogeneous oxide dispersions together with elongated grain structures. This information is required to develop sufficient understanding of the mechanisms responsible for elongated grain structure that guidelines might be written for producing these desirable micro-structures in oxide dispersion strengthened superalloys of interest to the Air Force.

Recent Progress and/or Plans: A fundamental investigation will be undertaken to determine the effects of oxide content, and thermal and mechanical history on the shapes and crystallographic orientations of recrystallized grains in various particle strengthened alloys (both model systems and Ni-Cr-Al systems).

References: None to date.

8.4 TITLE: Fundamental Investigation of Superplastic Forming Process

Technical Objective: The objective of this research is to clarify the mechanical and microstructural properties of structural alloys in superplasticity and creep processes. A better understanding of the dependence of superplastic strain rate on temperature, flow

stress, grain size and other microstructural details will be of significant help in optimization of processing variables. Such optimization will enable the material to be deformed at the ductility associated with superplasticity.

Recent Progress and/or Plans: Four areas are proposed for special study: (1) Consideration of microstructural modifications induced by superplastic flow and their effect on the mechanical properties of the superplastically deformed material; (2) Investigation of the nature of stress-strain data, activation energy, and threshold stress in low strain rate regions which correspond to the creep strain rates usually encountered in service of high temperature components, i.e., gas turbine engines; (3) Delineation of ranges of operation of superplastic processes, and study of the criteria for the transition from superplasticity to creep. In addition, investigation of the factors that would allow extension to higher strain rates and optimization of the processing parameters for forming operations. (4) Determination of the factors which lead to fracture during the superplastic process in terms of microstructural modification, cavitation and geometrical instability. During the first year, the areas outlined above will be investigated using a well characterized model system (Al-Zn eutectoid alloy). Subsequent effort will focus upon alloys with potentially important applications in the manufacture of airframes and engines (such as Ti-6Al-4V, a near-beta Ti alloy, IN-100, and a high strength aluminum alloy).

References: None to date.

8.5 TITLE: <u>Shear Bands in Forged Products</u>

Technical Objective: The objective of this investigation is to document experimentally the occurrence of shear bands in forged products and to validate analytical techniques for their prediction. In addition, the effect of shear bands on subsequent mechanical behavior before and after typical post-forging heat treatments will be established. The results of this program will lead to much needed understanding of effects and control of a common forging defect which is of vital interest to the Air Force.

Recent Progress and/or Plans: The research program will be performed over a 3-year period. In the first year, the mechanical properties of the program material will be determined, the applicability of heat transfer and combined heat transfer-deformation models established, and instability criteria evaluated in a simple deformation mode. During the second year, a simple and a more complex forging will be done to establish the validity of the heat transfer-deformation analysis and instability analysis to simulate more general deformation modes and to determine how these analyses should be used to predict process variables which lead to shear band development. Finally, the third year program will consist of mechanical testing to determine the effect of shear bands on in-service properties. In view of the ongoing program on the development of a science base for manufacture of a dual property compressor disk of Ti-6Al-2Sn-4Zr-2Mo, this alloy will be utilized. In addition, there is a general move away from the Ti-6Al-4V alloy towards other titanium alloys such as Ti-6Al-2Sn-4Zr-2Mo with improved performance at higher service temperatures.

References: None to date.

8.6 TITLE: Fatigue in Powder Metallurgy Aluminum Alloys

Technical Objective: The objective of this research is to establish and quantify processing-microstructure-mechanical behavior relationships in fully-dense powder metallurgy materials. Particular interest centers on fatigue response in aluminum-base alloys and includes the roles of stress state and environment. Since aluminum alloys form a major portion of the material currently used for skin and other structural airframe applications, it is appropriate that they are the basis of this investigation. The broader fundamental understanding of the fatigue behavior of aluminum alloys to be developed during the course of this research will provide the basis for carrying out future alloy and process development to achieve improved materials.

Recent Progress and/or Plans: Through a fundamental study, the influence of deformation processing, microstructure and alloy chemistry in a high strength aluminum P/M system (MA87) can be examined and correlated with attendant property alterations. To this end, the broad objectives are: (1) Establish the relationships between fatigue behavior, microstructure and alloy chemistry in powder processed high strength aluminum alloys. (2) Assess the influence of deformation mode and microstructure upon the fatigue initiation and propagation processes, to include material anisotropy and environmental effects. (3) Develop an understanding of the complex interplay of alloy chemistry, processing route, fatigue behavior and service environment in high strength aluminum alloy systems. Specifically, there are two concurrent phases: in one, the combined effects of powder processing mode and cobalt level (0, 0.4 or 0.8 wgt. %) are examined; in the other, the level of cobalt is kept constant (0.4 wgt. %) and the level of material flow during densification in plane strain forging of the powder preform is varied.

References:

"Fatigue of High Strength Aluminum-Alloy P/M Forgings," (M. Rafal in, M.J. Koczak and A. Lawley); Symposium on Thermomechanical Processing of Aluminum Alloys, AIME Fall Meeting (1978); to be published.

"Fatigue Behavior of Powder Metallurgy High-Strength Aluminum Alloys-The Role of Composition and Microstructure" - Ph. D. Topic (M. Rafalin).

"Role of Processing on the Fatigue Behavior of High Strength Powder Metallurgy Aluminum Alloys" - Ph. D. Topic (H.W. Antes).

8.7 TITLE: Fatigue Crack Initiation and Propagation in High Strength Aluminum P/M Alloys

Technical Objective: This research effort is to quantitatively determine in high strength aluminum (P/M) alloys fatigue crack initiation, rate of macrocrack growth, and plastic work of fatigue crack growth as a function of microstructural features. This research will contribute to the development of P/M aluminum alloys such as MA87 because the major operative fatigue mechanisms will have been investigated and better understood.

Recent Progress and/or Plans: The effect of intermetallics and oxides on fatigue crack initiation and fatigue crack propagation as a function of increased total hysteretic plastic work per unit area of measurement will be investigated.

References:

"Plastic Work During Fatigue Crack Propagation in a High Strength Low Alloy Steel and in 7050 Aluminum Alloy," S. Ikeda, Y. Izumi and M.E. Fine, Eng. Fract. Mech. 9, 123 (1977).

"The Hysteretic Plastic Work as a Failure Criterion in a Coffin-Manson Type Relation," J.S. Santner and M.E. Fine, Scripta Met. 11, 159 (1977).

"The Strength and Toughness of a Ceramic Reinforced with Metal Wires," J.C. Zwissler, M.E. Fine and G.W. Groves, J. Amer. Cer. Soc. 60, 390 (1977).

"The Effect of Temperature on the Fatigue Crack Propagation Rate in Aluminum," P.K. Liaw, M.E. Fine, M. Kiritani and S. Ono, Scripta Met. 11, 1151 (1977).

NASA INPUTS

9. NASA - Lewis Research Center
21000 Brookpark Rd.
Cleveland, OH 44135
(Dr. Hugh R. Gray)

9.1 TITLE: Evaluation of the Cyclic Behavior of Aircraft Turbine Disk Alloys

Technical Objective: Eight nickel-base superalloys representing various strength levels and processing histories were evaluated at 650°C to determine if recent advances in powder metallurgy alloy development have resulted in corresponding increases in low cycle fatigue capability.

Recent Progress and/or Plans: Waspaloy, Astroloy, NASA II B-7, IN100, Inconel 718 and Rene 95 were evaluated in wrought and powder metallurgy plus HIP forms. Generally, crack initiation lives were found to increase with increasing tensile yield strength, while resistance to fatigue crack propagation generally decreased with increasing strength. A follow-on program at PWA (NAS 3-21379) is currently underway (6/78 - 12/79) aimed at cross-comparing the test procedures and data sets generated in the two programs referenced below.

References:

"Evaluation of Cyclic Behavior of Aircraft Turbine Disk Alloys," Shahani, V., and Popp. H.G.; NASA-CR-159433, General Electric Company, June 1978.

"Evaluation of the Cyclic Behavior of Aircraft Turbine Disk Alloys," Cowles, B.A., Sims, D.L., and Warren, J.R., NASA-CR-159409, Pratt & Whitney Aircraft Group, October 1978.

9.2 TITLE: The Effect of Microstructure on Hydrogen Embrittlement of the Nickel-Base Superalloy, Udimet 700.

Technical Objective: To compare wrought and powder metallurgy forms of the same alloy, Unimet 700, for relative resistance to hydrogen embrittlement in order to understand the roles of grain size and grain boundary phases on the embrittling process.

Recent Progress and/or Plans: Two prealloyed powder metallurgy conditions of Udimet 700 were shown to exhibit significantly and hydrogen environment embrittlement, as compared to conventionally cast and wrought Udimet 700. No additional research in this area is planned.

References:

"Effect of Microstructure on Hydrogen Embrittlement of the Nickel-Base Superalloy Udimet 700," Gray, Hugh R., NASA-TM-73772, April 1978.

INDUSTRIAL INPUTS

10. Bell Aerospace Textron
P.O. Box No. 1
Buffalo, NY 14120
(Robert W. Hussa)

10.1 TITLE: Weldability of Formable Sheet Titanium Alloy Ti-15V-3Cr-3Al-3Sn

Technical Objective: Establish welding procedures and determine notched tensile strength fracture toughness, and flow growth rates of welds in the Ti-15V-3Cr-3Sn alloy.

Recent Progress and/or Plans: This program was completed under contract to the Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio, in December 1978.

References:

The final technical report on this contract (F33615-75-C-5232) will probably be published about April 1979.

10.2 Shear Spin/Form Fabrication of Titanium Alloy Pressure Vessels

Technical Objective: Develop a low-cost fabrication method for titanium alloy pressure vessels. Secondarily, to exploit the finer grain size achieved by shear spinning to obtain better heat treated properties and improved fracture behavior.

Recent Progress and/or Plans: This program was completed under contract to the Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio, in 1977. Future plans include production fabrication of tanks - several potential applications are now being considered.

References:

Final technical report AFML-TR-77-88.

11. Boeing Aerospace Company
P.O. Box 3999
Seattle, Washington 98124
(I.J. Stampalia)

11.1 TITLE: Research on Inhibition for Corrosion Fatigue of High Strength Alloys

Technical Objective: The objective of the program was to conduct an indepth study of oxidizing inhibitors to mitigate hydrogen embrittlement and/or stress corrosion cracking of high strength ferrous alloys in potentially corrosive atmospheres.

Recent Progress and/or Plans: The above contract will be completed on 9/78. Air Force is approached to extend the study for understanding the mechanism of corrosion inhibition and application methodology of promising inhibitors.

References:

Final Report #AFML-TR-78-178 on Contract #F33615-75-C-5200-1, 15 December 1978.

J.E. Finnegan, K.B. Das, and E.D. Verink, Jr., "The Stress Corrosion Cracking Behavior of High Strength Steel Alloys in Inhibited Solutions," Paper to be presented at the International Conference on Corrosion in Caracas, Venezuela, Feb. 1979.

Several more papers are under preparation for publication in scientific journals.

11.2 TITLE: Effect of Retained Austenite on Hydrogen Embrittlement of Steels

Technical Objective: The objective of the program was to investigate the possible role of retained austenites in ferritic lattice as traps to reduce the susceptibility of ultrahigh strength steels to hydrogen embrittlement.

Recent Progress and/or Plans: University of Oregon Graduate Center P.O. 15737 completed in September 1978 (OGC funded by U.S. Army Research Office). Follow-on P.O. No. 22676 awarded to study the stability of austenites under the influence of stress, hydrogen content, and compositional variables.

References:

W.E. Wood, K.B. Das, and P.A. Parrish, "The Influence of Microstructure on Hydrogen Embrittlement in High Strength Steel," Proceedings of the 2nd International Congress on Hydrogen in Metals held at Paris, France, June 1977, Session 3B3, pp. 1-7.

C.E. Bauer, K.B. Das, and W.E. Wood, "Effect of Retained Austenite on Hydrogen Embrittlement of Steels," to be published Metallurgical Transactions.

Two more papers are being prepared for publication in scientific journals.

12. Battelle
Columbus Laboratories
505 King Ave.
Columbus, Ohio 43201
(F.C. Holden)

12.1 TITLE: <u>Effects of Hot Forging Variables Upon Microstructure and Properties of Metals and Alloys</u>

Technical Objectives: To develop a fundamental understanding of hot forging by showing how complex strain, time, temperature histories affect material response.

Recent Progress and/or Plans: A combined metallurgical and mechanical study of hot forging is described. Theoretical predictions of strain and temperature distributions are compared with experimental observations for both ring and extrusion forgings. It is shown that a complete description of the process requires understanding of friction, heat flow, constitutive behavior (including both deformation and fracture), and of the basic equations of continuum mechanics. To a large extent the predictions agree with experiments although differences in fine detail are noted.

References:

(Direct Inquiries to: T. Altan) V. Nagpal, G.D. Lohoti, and T. Altan, "A Numerical Method for Simultaneous Prediction of Metal Flow and Temperatures in Upset Forging of Rings," ASME Paper 77-WA/PROD-35.

12.2 TITLE: <u>Laser Shock Processing</u>

Technical Objective: The objective of this research is to investigate the use of pulsed lasers to induce high-amplitude stress waves in materials and improve their fatigue properties.

Recent Progress and/or Plans: A program was initiated in July, 1978, with the Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Dayton, Ohio, to investigate the use of laser-generated shocks for improving the fatigue life of fastener regions of aluminum aerospace structures.

References:

Papers on laser shocking of metals and alloys to improve fatigue properties will appear in 1979.

13. Fairchild Republic Company
Farmingdale, L.I.
New York 11735
(A. Shames)

13.1 TITLE: <u>Cold Formable Titanium Sheet</u>

Technical Objective: The demonstration of the manufacturing producibility of titanium alloy 15V-3Cr-3Sn-3Al. This incorporates both the large scale manufacture of strip products as well as the development of mechanical property data, processing the development of mechanical property data, processing techniques, and the fabrication of aircraft complements.

Recent Progress and/or Plans: Recent studies at Fairchild Republic Company and earlier work sponsored by the United States Air Force indicate the potential for 15-3-3-3 to be used in applications requiring crack-resistant materials based upon preliminary crack growth tests conducted in air and salt water.

References: None to date.

14. Ford Aerospace & Communications Corp.
Aeroneutronic Division
Ford Road
Newport Beach, CA 92663
(Donald L. Walker)

14.1 TITLE: <u>HP9-4-30 Alloy Steel Carburized Gears</u>

Technical Objective: Achieve 200,000 psi (1380 MPa) minimum yield strength in the core of carburized alloys with dynamic fracture toughness, Kid, above 50 KSI-in$^{-1/2}$ (55 MPa-m$^{-1/2}$).

Recent Program and/or Plans: Investigations of properties of HP9-4-30 alloy steel after carburizing at 1700°F (925°C) and tempering between 275 and 300°F (135-150°C), revealed that dynamic fracture toughness greater than 50 KSI-in$^{-1/2}$ (55 MPa-m$^{-1/2}$), yield strength greater than 200,000 psi (1380 MPa) and tensile strength greater than 280,000 psi (1900 MPa) could be achieved with case hardness above 60R$_c$. Also, HP9-4-30 tempered at 400°F (204°C) rather than 1040°F (560°C) exhibited dramatic improvement in fatigue life during actual service tests.

References:

"HP9-4-30 Alloy Steel for High Strength Gears," D.L. Walker, Metal Progress, June 1978, pp. 54-57.

15. General Dynamics
Fort Worth Division
P.O. Box 748
Fort Worth, Texas 76101
(Richard E. Adams)

15.1 TITLE: Effects of Fasteners on Fuel Integrity and Improved Durability of Advanced Metallic Materials

Technical Objective: To improve the durability performance of fastened aluminum joints by reducing fretting and delaying crack initiation at fastener holes. This will be done by modifying hole manufacture and assemble procedures to eliminate features leading to rapid imitation.

Recent Progress and/or Plans: A 1979 IRAD program has been funded to try to improve structural integrity at fastener holes. For example, spotfacing of stackup interfaces at fastener hole locations will be evaluated for durability. This is intended to reduce fretting and to reduce through thickness stresses contributing to crack initiation. Other assembly and drilling variables will be tested as well to reduce the effect of particular crack initiation mechanisms. In addition, fastener to hole interference or clearance affect the local stress state. Fastener type and hole tolerance will be varied as part of this program to achieve optimum retardation of fatigue crack initiation.

References:

An engineering report will be published at the completion of this work.

15.2 TITLE: Fastener Hold Quality, Air Force Flight Dynamics Laboratory (AFFDL) F33615-76-C-3113

Technical Objective: To establish the cause of variation in fatigue life of aluminum structure containing fastener holes and to provide methods for controlling the life of individual fastener holes during their manufacture.

These objectives were accomplished by the modification of automatic drilling equipment which, upon withdrawal of the tool from the fastener holes, were producing axial scratches not visible to the naked eye that were initiating fatigue cracks. The modifications to the drilling equipment decreased the rate of retraction from the holes while maintaining rotation of the drill bit until fully retracted from the fastener holes. These modifications have extended the life, at the time for cracks to grow to 0.030 inch, for aluminum structure from 10,500 hours to 14,500 hours for drilled fastener holes over drilled and reamed fastener holes.

Recent Progress and/or Plans: (A) Currently in process of implementing "improved" drilling on F-16 production line for drilling of all wing skins and wing subassemblies. (B) Extending this technology via development of a Durability Methods Design Handbook under current AFFDL Contract F33615-77-C-3123 "Durability Methods Development." (C) Applying improved drilling and assembly techniques to the F-16 structure to yield increased durability and reduce cost.

References:

Noronha, P.J., et al, Fastener Hole Quality, AFFDL-TR-78-208 Volume I and Volume II, Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio, December 1978.

15.3 TITLE: Evaluation of HIPped Ti-6Al-4V Alloy Powder Mechanical-Metallurgical Properties

Technical Objective: To evaluate the effect of processing and subsequent thermal treatments upon the properties, e.g., fracture toughness, crack growth rates, etc., of consolidated titanium powder.

Recent Progress and/or Plans: The fracture toughness and crack growth rate of the HIPped titanium was determined for several thermal conditions. These preliminary investigations reveal different thermal response of powder product from the wrought forms. Continuing efforts will be directed toward optimizing thermal treatments consistent with improved properties.

References:

ERR-FW-1864 Properties of Forged and HIPped Ti-6Al-4V Titanium Alloy

ERR-FW-1989 Mechanical/Metallurgical Properties of a HIP Ti-6Al-4V Alloy Powder Compact.

15.4 TITLE: Development of a High Strength/High Toughness Steel Alloy

Technical Objective: To develop a high strength (230-250 Ksi TUS) fracture resistant steel with good crack growth and stress resistance as a replacement for the Ti-6Al-4V alloy in airframe applications.

Recent Progress and/or Plans: Successful alloy modification program resulted in the development of AF 1410 steel which proved to possess superior crack growth and stress corrosion resistance. On-going studies are addressing the effect of variable thermal processing on these properties.

References:

AFML-TR-75-148 "Development of a Weldable High Strength Steel."

ERR-FW-1988 "Preliminary Study of Monotonic and Cyclic Mechanical Behavior in High Toughness Alloys."

15.5 TITLE: <u>Aluminum Powder Metallurgy</u>

Technical Objective: To determine the crack growth rate and fracture resistance of mechanically alloyed aluminum powder in ambient and aggressive environments.

Recent Progress and/or Plans: Plans - To determine the mechanical and thermal processing of aluminum alloy powder forms concomitant with optimum fracture toughness, stress corrosion, HC and LC fatigue, and crack growth rate properties.

References: None to date.

15.6 TITLE: <u>Evaluation of 304L Stainless Steel</u>

Technical Objective: Determine the static critical crack intensity factor (Kic) and flaw growth of 304L parent metal & weldments at room temperature and $20^{\circ}K$.

Recent Progress and/or Plans: This study was conducted under the large coil program (superconducting magnet) at General Dynamics/ Convair.

References:

Internal GD/C Memos during 1978.

16. Lockheed Palo Alto Research Laboratory
3251 Hanover Street
Palo Alto, CA 94304
(T.E. Tietz)

16.1 TITLE: <u>Development of Advanced Aluminum Alloys From Rapidly Solidified Powders for Aerospace Structural Applications</u>

Technical Objective: To develop improved alloys from rapidly solidified powders that exhibit as primary goals (a) a 30% increase in elastic modulusto-density ratio (E/ρ), or (b) a 20% increase in E/ρ. and a 20% increase in strength compared to 7075-T76 Al alloy, without significant loss in other properties. Goals will also include optimization of fracture toughness and fatigue properties.

Recent Progress and/or Plans: Program consists of three phases: Phase I - Fundamental Alloy and Process Studies, Phase II - Scale-Up and Evaluation of Simple Mill Forms, and Phase III - Design Trade-Off Evaluation. Phase I - Fundamental Alloy and Process Studies over a two year period will involve the Alcoa Research Laboratories and Georgia Institute of Technology as well as the Lockheed Palo Alto Research Laboratories.

References:

"A Feasibility Study for Development of Structural Aluminum Alloys From Rapidly Solidified Powders for Aerospace Structural Applications," by R.E. Lewis, D. Webster, and I.G. Palmer, AFML-TR-78-102, July 1978.

16.2 TITLE: Advanced Aluminum Alloys

Technical Objective: To develop advanced aluminum alloys with increased structural efficiency utilizing rapidly solidified powders.

Recent Progress and/or Plans: The program plan includes investigation of (1) ordering and precipitation reactions in high-modulus alloys, and (2) use of duplex composition alloy powders to increase toughness in high-modulus, high-strength alloys.

The 1979 program will study alloys containing dispersoid-forming elements in Al-Li alloys to promote increase in fracture toughness.

Selected alloys will be studied produced from different compositions of rapidly solidified powders consolidated to produce controlled duplex microstructures to increase fracture toughness.

References: None to date.

16.3 TITLE: Thermomechanical Shear Forming of Aluminum Alloys

Technical Objective: Demonstrate feasibility of applying thermomechanical working concept to the shear forming of aluminum alloy near-net shapes using 2219 and 6061 as model materials. Specifically, the goal is to develop combined warm working-aging procedures for these alloys which will significantly reduce pressure vessel manufacturing costs and improve product performance capabilities.

Recent Progress and/or Plans: Explore variety of thermomechanical shear forming sequences and establish optimum procedure for specific alloy based on correlative microstructural, anisotropy, and mechanical property (tensile, K_{IC}, K_{ISCC}) evaluation studies.

References:

E.H. Rennhack, "How Normal Anisotropy Influences Formability of Aluminum Alloys," Met. Eng. Quart., 1976, vol. 16, p. 58.

16.4 TITLE: Shear Formability of Ti-6Al-4V Plate

Technical Objective: Establish the influence of the average plastic strain ratio on shear form press performance and identify potentially promising processing procedures that will alter normal anisotropy in a favorable manner and provide a significant improvement in metal formability and properties.

Recent Progress and/or Plans: Elevated temperature anisotropic behavior of Ti-6Al-4V plate was determined and correlated with the microstructure, texture, properties, and burst performance of 56-cm-diam. pressure vessels fabricated from warm shear spun hemispheres. Thermomechanical processing procedures which facilitate texture strengthening in combination with age hardening currently are being sought. Fracture studies are planned to determine K_{IC}, K_{ISCC}, and da/dn in various environments.

References:

E.H. Rennhack and D.D. Crooks, "Elevated Temperature Plastic Anisotropy of Ti-6Al-4V Plate," Met. Trans. A, in press.

17. McDonnell Douglas Research Laboratories
St. Louis, MO 63166
(C.R. Whitsett)

17.1 TITLE: Corrosion-Fatigue Behavior of Powder-Processed Al-Cu-Li Alloys

Technical Objective: Determine the fatigue-crack initiation and propagation behavior in low-density, high-modulus, high-strength Al-Li-based alloys as a function of environment and microstructure.

Recent Progress and/or Plans: Al-1.5Cu-2.5Li-0.5Mn alloy will be processed by gas-atomization into powder, which will be consolidated by hot extrusion. Appropriate heat treatments will be employed to vary the characteristics of strengthening precipitates, and the fatigue properties of the heat-treated alloys will be measured in aggressive and benign environments, including NaCl solution, humid air, and pure Ar. The fatigue characteristics will be analyzed on the basis of the alloy microstructures.

References:

Independent Research and Development Program Descriptions. McDonnell Douglas Report MDC Q0853-4, Vol. I. Metal Physics-Strength and Corrosion, pp. 94001.01 ff. (1979).

17.2 Diffusion Bonding of Textured Ti-6Al-4V

Technical Objective: Evaluate the potential of diffusion bonding cross-laminated, sharply-textured, Ti-6Al-4V sheets to achieve high isotropic-strength and toughness.

Recent Progress and/or Plans: The crystallographic texture produced by rolling titanium alloys causes a large anisotropy of tensile strength and fracture toughness. Undirectionally-rolled, sharply transverse-basal-textured Ti-6Al-4V sheets will be diffusion bonded into plates with the rolling direction of alternate layers at different angles. The tensile strength and fracture toughness as functions of direction in the built-up plates will be compared with conventionally processed Ti-6Al-4V plates. The potential of this fabrication process for applications requiring high isotropic-strength and toughness will be determined.

References:

Independent Research and Development Program Descriptions. McDonnell Douglas Report MDC Q0849-4, Vol. I. Metal Physics-Strength and Corrosion, pp. 84001.01 ff. (1978).

Independent Research and Development Program Descriptions. McDonnell Douglas Report MDC Q0583-4, Vol. I. Metal Physics-Strength and Corrosion, pp. 94001.01 ff. (1979).

17.3 TITLE: Improvement of the Weld Strength of Ti-6Al-4V Alloy

Technical Objective: Determine the weldability and weld strength of Ti-6Al-4V containing Er or Y additives using conventional and rare-earth modified filler metal.

Recent Progress and/or Plans: Standard production methods will be used to butt-weld 3-mm thick sheets of Ti-6Al-4V, Ti-6Al-4V-0.02Y, Ti-6Al-4V-0.04Y, Ti-6Al-4V-0.04Er, and Ti-6Al-4V-0.3Er. The filler-metals to be tested are pure Ti, Ti-0.02Y, Ti-0.09Y, Ti-0.05Er, Ti-0.27Er, Ti-6Al-4V, Ti-6Al-4V-0.02Y, Ti-6Al-4V-0.04Y, Ti-6Al-4V-0.04Er, and Ti-6Al-4V-0.34Er. Prior to welding, the plates will be annealed at 715-790°C for 1 h and air cooled to room temperature. Following automatic TIG welding, the assemblies will be stress relieved at 620-775°C and air cooled to room temperature. The welds will be characterized by visual examination, optical and electron microscopy, penetrant inspection, radiography, and mechanical testing.

References:

Independent Research and Development Program Descriptions. McDonnell Douglas Report MDC Q0853-4, Vol. I. Metal Physics-Strength and Corrosion, pp. 94001.01 ff. (1979).

17.4 TITLE: Influence of Rare-Earth Additions on the Suppression of Titanium Hydride Precipitation in Titanium and Titanium Alloys

Technical Objective: Determine the effectiveness of Erbium and Yttrium additions for suppressing titanium hydride precipitation in titanium alloys.

Recent Progress and/or Plans: Small additions (0.1-1wt%) of erbium and yttrium to titanium decrease the density of titanium hydrides by preferential gettering of hydrogen. Presently, the hydride suppression by Er and Y additions is being studied in two nearly single-phase commercial titanium alloys, Ti-6Al-2.5Sn (alpha alloy) and Ti-15V-3Al-3Sn-3Cr (beta alloy). Samples of the two alloys will be charged to 100-1000 p.p.m.H_2, appropriately annealed to effect homogenization, and slowly cooled to precipitate TiH_2. The density and distribution of TiH_2 precipitates and the Er and Y dispersoids will be determined by quantitative metallography and transmission electron microscopy. Specimens of the alloys in the charged and uncharged conditions will be tested underuniaxial tension, and the results will be analyzed to establish the effect of Er and Y on suppression on TiH_2 precipitation and hydrogen embrittlement.

References:

R.J. Lederich, J.E. O'Neal, and B.B. Rath, "On the Precipitation of Hydrides in Alpha-Titanium and Titanium-Erbium Alloys," Materials Engineering Congress, American Society for Metals (1973), p. 125.

Independent Research and Development Program Descriptions. McDonnell Douglas Report MDC Q0835-4, Vol. I. Metal Physics-Strength and Corrosion, 1120-01 ff.(1974).

Independent Research and Development Program Descriptions. McDonnell Douglas Report MDC Q0841-4, Vol. I. Metal Physics-Strength and Corrosion, pp. 4001.01 ff. (1979).

Independent Research and Development Program Descriptions. McDonnell Douglas Report MDC Q0853-4, Vol. I. Metal Physics-Strength and Corrosion, pp. 94001.01 ff. (1979).

18. Pratt & Whitney Aircraft Group
P.O. Box 2691
West Palm Beach, FL 33402
(M.C. VanWanderham)

18.1 TITLE: Production of Powder Metallurgy Superalloy Turbine Disks

Technical Objective: The objective of this program is to apply the principle of rapid solidification to superalloy powders subsequent development of a strong alloy composition for jet engine turbine air-foils. Centrifugal atomization and forced corrective cooling are being used to produce the fast cooled material.

Recent Progress and/or Plans: F33615-75-C-5108.

References: AFML TR-76-101.

18.2 TITLE: Near Term, Near Net Shape Superalloy Disks

Technical Objective: Establish a reproducible manufacturing process for the production of near net disk, seal, and spacer shapes by advanced isothermal forging techniques.

Recent Progress and/or Plans: F33615-75-C5184.

References: AFML-TR-77-80.

18.3 TITLE: Titanium Damage Tolerant Design Data for Propulsion Systems

Technical Objective: Determine the fracture mechanics design properties for three titanium alloys: Ti 6246, Ti 6242, Ti 8-1-1.

Recent Progress and/or Plans: F33615-75-C-5130.

References: AFML TR-77-101.

19. Rockwell International Science Center
P.O.Box 1985
Thousand Oaks, CA 91360
(Neil E. Paton)

19.1 TITLE: Mechanical Behavior of Airframe Materials

Technical Objective: To investigate the recrystallization processes which have been found to produce grain sizes in high-strength aluminum alloys; and to evaluate the advantages in mechanical properties and corrosion resistance which may derive from the reduction in grain size.

Recent Progress and/or Plans: The production of fine grain sizes by recrystallization following cold deformation has been shown to result from the nature of the precipitate distribution present during the deformation. A detailed analysis of the roles of precipitates of various types and sizes during the deformation and crystallization is underway. This knowledge will aid in optimizing the thermal and mechanical treatment used to produce the fine grain sizes and in extending these processing techniques to other alloys. The reduction in grain size has been found to produce no significant increase in room temperature tensile properties, although high temperature ductibility is dramatically increased. Fatigue and corrosion properties are presently being evaluated to determine whether significant improvements result from the substantial grain refinement.

References: None to date.

19.2 TITLE: Fatigue and Fracture of Titanium Alloys

Technical Objective: To improve the fatigue crack propagation resistance and fracture toughness of titanium alloys through control of chemistry, processing and microstructure; and to understand the cracking behavior of titanium containing internal hydrogen or in the presence of corrosive environments.

Recent Progress and/or Plans: AFML program on fatigue crack propagation in Ti-6Al-4V and Ti-6Al-2Sn-6Mo demonstrated effect of microstructure on crack propagation and toughness.

IR&D program demonstrated accelerated crack growth in Ti-6Al-4V containing 100-300 ppm hydrogen both at room temperature and $-70^{\circ}C$.

References:

J.C. Chesnutt, A.W. Thompson and J.C. Williams, "Influence of Metallurgical Factors on the Fatigue Crack Growth Rate in Alpha-Beta Titanium Alloys," AFML-TR-78-68, May 1978.

19.3 TITLE: Laser and Electron Beam Processing of Materials

Technical Objective: Enhance mechanical properties through controlled surface treating methods such as lasers and electron beams. The methods are transformation hardening, alloying, cladding, glazing and grain refinement.

Recent Progress and/or Plans: Laser Processing of steels and super alloys.

References:

D.S. Gnanamuthu, C.B. Shaw, Jr., W.E. Lawrence, and M.R. Mitchell, "Laser Transformation Hardening," American Institute of Physics Conferences Proceedings, 31 Jan 1979.

20. Rockwell International Corporation
Columbus Aircraft Division
4300 E. Fifth Ave.
P.O. Box 1259
Columbus, OH 43216
(J.P. Fosness)

20.1 TITLE: Noble Metal Ion Implantation/Plating of Titanium Alloys

Technical Objective: Improved High Temperature Capability of Titanium Alloys.

Recent Progress and/or Plans: Noble metal ion plating provides an oxygen diffusion barrier. The prevention of surface oxidations believed to retard the formation of surface microcracking with a resulting substantial increase of high temperature ($850^{\circ}F$) fatigue life as reported by S. Fujishiro. The Columbus Aircraft Division has also demonstrated a substantial increase in compression creep crippling strength of platinum ion plated Ti-6Al-2Sn-4Zr-2Mo at temperatures up to $1100^{\circ}F$.

References:

Fujishiro, S. and D. Eylon, "Improved High Temperature Capability of Titanium Alloys by Ion Implantation/Plating, S&E Symposium, co-sponsored by AFSC and NAVMAT, October 1978.

Fujishiro, S., D. Eylon, and R.W. Gehring, "Improvement of Creep Properties in + Titanium Alloys by Pt Ion Plating, to be presented at the International Conference on Metallurgical Coatings, 6th International Vacuum Metallurgy Conference, San Diego, CA, 23-27 April 1979.

21. Rockwell International
International Airport
Los Angeles, CA 90009
(H. Raiklen)

21.1 TITLE: AF1410 Steel, a Low-Cost Substitute for Titanium

Technical Objective: To continue the development of a high strength, high toughness steel which is weldable and possesses a K_{IC} of 130 ksi in at a minimum yield strength of 220 ksi for applications as a fastener and critical structure material.

Recent Progress and/or Plans: Program completed in 1978 which demonstrated that AF1410 Steel could be substituted for large annealed Ti-6Al-4V fittings with a cost and weight savings (equal or superior toughness and strengths when ratioed to density).

References:

Little, C.D. and Machameier, P.M., "Development of a Weldable High Strength Steel," Final Report, AFML-TR-75-148, September 1975.

Routh, W.E., "Lower Cost by Substituting Steel for Titanium," Interim Report, AFFDL-TR-77-73, June 1977.

Parker, D., Bennett, G., and Robelotto, R., "Lower Cost by Substituting Steel for Titanium," Final Report, AFFDL-78-186, December 1978.

21.2 TITLE: Structural Verification of CORONA-5 High Fracture Toughness Titanium Alloy

Technical Objective: To demonstrate improved damage tolerance capability of a current aerospace component fabricated from CORONA-t, by full scale and element testing. To determine weight savings from design refinement and to establish material and fabrication cost comparisons with current design.

Recent Progress and/or Plans: None.

References:

Berryman, R.G., Froes, F.H., Chesnutt, J.C., Rhodes, C.G., Williams, J.C., and Malone, R.F., Final Engineering Report, Naval Air Systems Command Contract N00019-73-C-0355, "High Toughness Titanium Alloy Development," TFD-74-657, July 1974.

Berryman, R.G., Froes, F.H., Chesnutt, J.C., Rhodes, C.G., Williams, J.C., and Malone, R.F., Final Engineering Report, Naval Air Systems Command Contract N00019-74-C-0273, "High Toughness of Titanium Alloys," TFD-75-640, July 1975.

Berryman, R.G., Chestnutt, J.C., Froes, F.H., and Rhodes, C.G., Final Engineering Report, Naval Air Systems Command Contract N00019-75-C-0208, "High Toughness Titanium Alloy Development," TFD76-471, June 1976.

21.3 TITLE: <u>Improved Fracture Toughness (K_{IC}) in Titanium-6Al-4V Alloy</u>

Technical Objective: To improve the fracture toughness and fatigue crack growth behavior by controlling chemistry and microstructure over those properties observed in the mill annealed or STA condition. Additional work in modifying microstructure for even greater property improvement is indicated.

Recent Progress and/or Plans: (1) B-1 Program: The use of ELI and low Fe and Al chemistries coupled with a recrystallization annealed (RA) heat have shown significant improvement in toughness and fatigue crack growth behavior.

References: None to date.

21.4 TITLE: <u>Improved Fracture Toughness (K_{IC}) in PH 13.8 Mo Steel</u>

Technical Objective: To improve the plain strain fracture toughness (K_{IC}) and stress corrosion cracking resistance (K_{ISCC}) of PH 13.8 Mo steel while maintaining 220 ksi ultimate tensile strength.

Recent Progress and/or Plans: (1) Company IR&D Program: Control thermal-mechanical processing, and (2) B-1 Program: Heat treatment and chemistry.

References: NA-75-219 - Enclosed.

22. Thiokol
Government Systems Group
P.O. Box 9258
Ogden, UT 84409
(T.F. Davidson)

22.1 TITLE: <u>Space Shuttle Solid Rocket Motor Metal Case Component</u>

Technical Objective: The solid rocket motor cases were fabricated of Ladish DGAC steel at 195/220 ksi ultimate strength. To consistently achieve the fracture toughness requirement necessitated changes in the forging supplier's thermal processing and development of the final heat-treat cycle.

Recent Progress and/or Plans: Fabrication and heat-treat cycles resulted in meeting a 90 ksi IN fracture toughness requirement. Marginal success was achieved in the initial phases of the development program, and improvements resulted in components consistently meeting fracture toughness requirements.

References:

C.H. Krummel, and O.N. Thompson, "Space Shuttle Solid Rocket Motor Metal Case Components," AIAA Publication 78-752.

23. TRW
Defense and Space Systems Group
One Space Park
Redondo Beach, CA 90278
(G.G. Kaeding)

23.1 TITLE: Preplating Surface Sensing

Technical Objective: Quantification of surface for subsequent electro-deposition, adhesive bonding, or resistance welding to take preprocessing away from emperial development, and to also permit a controlled process.

Recent Progress and/or Plans: Recent program evaluated possible techniques for study but no program with depth accomplished. Plans to study this year were cancelled due to higher priority work.

References: None to date.

23.2 TITLE: Aluminum Costing of High Strength Aluminum Alloys Susceptible to Stress Corrosion

Technical Objective: Pure aluminum reduces stress corrosion cracking on high strength alloys such as 7075 and 2024. Sheet stock is supplied clad but machined parts of 7075 & 2024 that need protection can use the pure al plating.

Recent Progress and/or Plans: Over 1100 parts were electroplated with aluminum on Viking Mar Lander Biological Experiment. While we have no plans if a similar condition developed, TRW would consider using the same method.

References: None to date.

23.3 TITLE: Ion Beam Technology

Technical Objective: Develop processes for surface texturing of materials to enhance specific substrate properties.

Recent Progress and/or Plans: Applications derived from the use of broad beam electron bombardment ion sources were investigated.

References:

NASA CR-159437. "Ion Beam Technology Applications Study." J.M. Sellen, S. Zafran, and G.K. Komatsu. Final Report, Contract NAS 3-21027, November 1, 1978.

24. Vought Corporation
Advanced Technology Center, Inc.
P.O. Box 6144
Dallas, TX 75222
(A.P. Martin)

24.1 TITLE: Metal Laminate Development for Structures

Technical Objectives: To demonstrate improved fracture toughness and damage tolerance in thick aluminum, titanium and steel structures through the concept of metal/metal lamination. The specific concept is based on the retention of full sheet toughness in the laminated thick structural component.

Recent Progress and/or Plans: Vought Advanced Technology Center is now in the third year of activity under contract to Naval Air Systems Command. The plans for FY 1979 are to investigate application to damage tolerant structures made from high strength - low ductibility aerospace alloys with emphasis on steel and titanium.

References:

"Fracture and Fatigue of Diffusion, Explosive, and Roll Bonded Al/Al and Ti/Al Laminates," R.D. Goolsby, 13 May 1977 ADA-040387.

"Fracture and Fatigue of Diffusion, Adhesive, and Roll Bonded Aluminum, Titanium, and Ultrahigh Carbon Steel Laminates," R.M. Johnson, 16 June 1978 AD/A058553.

"Diffusion, Roll and Explosive Bonding of Al/Al, Ti/Al and Ti/Ti Laminates," R.M. Johnson, R.D. Goolsby and D.H. Petersen, Proceedings 10th National SAMPE Conference, October 17-19, 1978, Kiamesha Lake, New York, pp. 802-809.

25. United Technologies Research Center
East Hartford, CT 06108
(E.R. Thompson)

25.1 TITLE: Advanced Laser Processing of Materials

Technical Objective: Develop process for depositing material sequentially in thin, rapidly-quenched layers to provide a buildup of a specially designed high strength nickel alloy.

Recent Progress and/or Plans: A program funded by the Office of Naval Research is underway which will lead to the fabrication of a suitable alloy (and subsequent evaluation) into a small scale-model gas turbine disk configuration. An IR&D program which is exploring other potential applications of laser processing of materials is also continuing.

References:

Greenwald, Breinan and Kear, "Heat Transfer Properties and Microstructure of Laser Melted Alloys," Proceedings of 1978 Materials Research Society, Boston, MA, November 1978.

Kear, Breinan and Thompson, "Laser Processing of Materials," Proceedings, 25th Sagamore Army Materials Res. Conference, Bolton Landing, NY, July 1978.

Breinan and Kear: "Rapid Solidification Laser Processing Materials for Control of Microstructure and Properties," Proceedings of Conference on Rapid Solidification Processing, Claitors Publishing Div., Baton Rouge, LA, pp. 87-103 (1978).

25.2 TITLE: <u>Ion Implantation</u>

Technical Objective: To investigate the effects of ion implantation on the wear and fretting behavior of titanium.

Recent Progress and/or Plans: Experiments to determine the relative effects of the implantation of carbon, nitrogen and boron are to be conducted under this IR&D program. Parameters of interest include the effect of ion fluence, implantation energy, temperature during implantation, and post implantation annealing.

References: None to date.

25.3 TITLE: <u>H.I.P. Nickel-Based Superalloy Powders</u>

Technical Objective: To evaluate the structure and properties of rapidly-quenched, nickel base alloys for turbine disk applications.

Recent Progress and/or Plans: Hot isostatic pressing of powdered nickel alloys will be evaluated to determine their creep rupture characteristics and their fatigue crack initiation and crack growth behavior.

References: None to date.

V. EMERGENT R&D OPPORTUNITIES

Survey Highlights

The aggregation of projects reported in the previous chapter of this report constitutes a formidable R&D effort in both scope and magnitude. Many new and innovated approaches are identified to improve the crack tolerant properties of high strength alloys. These efforts can be classified into the following categories: alloy development, processing and fabrication, post processing heat treatment and surface modification. Several representative examples of these R&D opportunities are discussed below. As originally intended, extended discussions are given on two surface modification techniques, ion implantation and laser processing, in the two following sections of this chapter.

One of the most pervasive R&D activities reported in the survey is the investigation of powder metals in the development, processing, and fabrication of high strength alloys. The Army is sponsoring a significant exploratory development effort in the powder metallurgy of aluminum alloys (see Chapter IV, items 1.1, 1.2, 1.3, 1.4). The Navy, Air Force and several aerospace firms report basic and exploratory development programs (see Chapter IV, items 4.2, 6.5, 7.2, 8.6, 8.7, 15.5, 16.1, 16.2) in the powder metallurgy of superalloys (see Chapter IV, items 8.1, 9.1, 25.1) and aluminum alloys. Two responses were received on the development of titanium powder metallurgy (see Chapter IV, items 1A.6, 15.3).

The interest in powder metallurgy products is spurred by the potential to improve, at lower cost, the mechanical and crack tolerant properties of these alloys over their conventional wrought, casted, and forged counterparts. These improvements in basic material and product properties are achieved through control of segregation and microstructure, elimination of massive phases, extended alloy solubility, and near-net shape fabrication.

The work on superalloy powders has been stimulated in part by an improved powder production technique developed by Pratt and Whitney (see Chapter IV, item 18.1). Reportedly, superior superalloy powders are produced at solidification and cooling rates in excess of 10^5/sec. These rapid solidification rates (RSR) are achieved by forced convective cooling, whereby liquid particles of controlled size are accelerated into high thermal conductivity gaseous medium. Current work under DARPA sponsorship is seeking to refine the process and to apply the technology of rapid solidification to alloy development for gas turbine applications.

Another unifying theme in the survey is the development of rational principles of metallurgical optimization of crack tolerant properties (see Chapter IV, items 4.1, 5.5, 5.6, 19.2). The work of Yoder and co-worker (see Chapter IV, item 5.5) on the improved fatigue crack resistance of titanium alloys is a notable example of this approach. Through microstructural modification by post processing heat treatment, the fatigue crack growth resistance in commercial Ti-6Al-4V and Ti-8Al-1Mo-1V alloys have been improved by over an order of magnitude. Moreover, the improvements in properties can be rationalized in terms of the microstructural modification and the crack tip stress state as defined by the ΔK parameter. In

this as well as other studies, fracture mechanics characterization plays an important quantitative role in the metallurgical optimization of crack tolerant properties. AF1410 steel (see Chapter IV, items 15.2, 21.1) and CORONA-5 titannium (see Chapter IV, item 21.2) are examples of modern alloy development based on fracture mechanics parameters.

A corollary to the role of fracture mechanics in the development of high strength alloys is the requirement for a balance of properties in candidate alloys. Modern design and alloy selection criteria usually must consider all phases of the damage process of crack initiation, subcritical crack growth, and fracture. Moreover, the potential now exists to optimize metallurgically both the bulk controlled properties (e.g., subcritical crack growth and fracture) and the surface controlled properties (e.g., crack initiate) by combining surface modification techniques with one or more of the other approaches listed above. Two of the most promising surface modification techniques, ion implantation and laser processing, are reviewed in detail in the following sections.

Ion Implantation of Materials

Ion implantation in metals and alloys has experienced a rapid growth during the past few years. Since early 1970's there has been a significant number of articles, papers, books and conferences devoted to non-electronic properties of ion implanted materials (Ref. 11). Surface related properties such as friction, wear, corrosion and fatigue-life of structural metals and alloys are found to improve as a result of ion implantation. Almost all surface-sensitive, life-limiting properties of structural materials can be modified by ion implantation. Furthermore, ion implantation has several advantages such as: (1) the method is independent of diffusion-controlled processes and thus surface chemistry can be modified to any desired fluence with any chemical species, (2) bulk properties related to strength and toughness can be maintained at the desired values while optimizing the surface chemistry and microstructure without a sharp interface and (3) use of relatively scarce metals can be minimized through surface alloying by ion implantation.

Ion implantation is a process of accelerating ions to high velocities and directing them into the near-surface regions of metals and alloys to produce in essence a different alloy in the near-surface region. The method can indeed be utilized to produce a graded alloy from the surface to the unchanged underlying bulk. Since the method is distinctly different from coating or plating processes, there are no problems relating to adhesion or change of microscopic dimensions. The apparatus consists of an acceleration which produces a high energy ion beam (usually at tens to hundreds of kilovolts) of any preselected element. These ions are forcibly injected beneath the surface of any material. This injection process produces an intimate alloy of the implanted and the host elements without producing a sharp interface characteristic of all coating processes. The resultant depth distribution and alloy composition depend on the energy and the atomic number of the projectile as well as on the atomic number of the host.

Typically, depths of hundreds to thousands of angstroms are achievable with concentrations of up to 50%. Since it is not a thermodynamic process, metastable alloys can be formed without regard for solid solubility or diffusivity. However, if chemical equilibrium is required, it can be achieved by a suitable post heat-treatment. Depending on the characteristics of the host metal and the implanted ion metastable phases including amorphous structures could be formed on the surface of crystalline substrates.

Hardness: Several investigators have reported a significant increase in surface hardness of alloys resulting from ion implantation. Of course it should be recognized that these hardness values are determined by measuring the Vickers or Knoop hardness number, which consists of making diamond indentations several times deeper than the thickness of the implanted layer, and therefore, do not precisely represent the implanted surface hardness.

Most experiments have been done in pure ion or steels implanted with carbon, nitrogen, argone and boron (Ref. 18, 19). In all cases the surface microhardness improved due to implantation. The observed surface hardening has been related to the probable formation of carbides or nitrides or to the radiation induced damage effects. It is interesting to note that inert gases such as Ar and Ne have no effect when implanted above $500^{\circ}C$, whereas room-temperature implantation produces hardening. Boron-implanted beryllium substrates shows significant promise for use in precision gas-bearing components. These components currently in use have a hard oxide coating which exhibit adhesion problems.

Friction: Most of the work, all very preliminary, on the effect of ion implantation on friction has been conducted at Harwell. Measurements of friction force between a tungsten carbide ball and case-hardened steel (EN 352) implanted with Mo, Sn, Pb, In and Kr at fluences between 10^{16} and 10^{17} ions/cm^2 show encouraging results. The results show no effect of Kr, an increase for Pb and a decrease for Sn both by as much as 50% (Ref. 17).

Overlapping implantation of Mo and S significantly reduced friction presumably due to the formation of MoS_2. Ion implantation does provide a novel method of forming near-surface precipitates known for their solid-lubricant properties on a hard, wear resistant material.

Wear: Probably the most extensive study has been directed to study the improvement of wear due to ion implantation. Most of the wear tests have been carried out with a pin-on-disk test under lubricated conditions. The wear rates of the rotating implanted disks were found to be significantly reduced by as much as a factor of 30. Wear rates of several steels and bearing alloys implanted with N, C, Ar, Mo and Co has been determined by this method.

Recent investigation at NRL shows resistance of type-416 stainless steel and AISI-52100 steel due to an implantation of nitrogen to a fluence level of $2x10^{17} N^+/cm^2$ at 50 keV (Ref. 20).

Several analytical techniques are currently being used for the investigation of the implantation effects on wear. These techniques include Mossbauer spectroscopy, Auger electron spectroscopy, transmission electron microscopy, scanning electron microscopy and wear particle analysis (Ref. 21). Results comparing the

unimplanted and implanted couples indicate that there is no significant change in the shape or size distribution of the wear particles produced even though they differ in quantity by a factor as high as several hundred. Although the fundamental features of the responsible mechanisms are not understood as yet, the results suggest that implantation reduces the initiation and growth rates of cracks formed during the wear process. Significant industrial application of the process to reduce wear of moving components has already occurred. Some of these are implantations of: (1) cutting knives for paper and rubber, (2) high-speed taps for phenolic plastics and (3) cemented tungsten-carbide tools, wire-drawing dies and forming tools (Ref. 22).

Fatigue: Fatigue life-times of stainless steels, titanium, titanium alloys (Ti-6Al-4V) and maraging steels have been shown to improve by 8-10 times by ion-implantation with nitrogen (Ref. 17). Aging after implantation improves fatigue-life presumable due to the formation of nitrides. Electron microscopic study shows that large concentrations of 10nm precipitates of $Fe_{16}N_2$ form at the near-surface region of the samples which delays crack nucleation at the surface. Further investigation is required to establish the mechanism for the improvement of fatigue-life of alloys.

Oxidation and Corrosion: Ion-implantation has been shown to have a profound effect on the oxidation and corrosion of metals and alloys. Oxidation rates of chromium-rich stainless steels are significantly reduced by implantation of Yttrium and other rare-earth ions (Ref. 22). Similar results have been reported for titanium implanted with Ba, Ca and Eu (Ref. 23). Thermal oxidation was reduced at all temperatures. The parabolic rate constant for oxidation of FeCrAlY alloy was reduced because of Al ion implantation by a factor of 140. Experiments have indeed shown that pure iron ion implanted with Cr and Ni exhibit corrosion resistance identical to stainless steels of comparable bulk composition.

These results show that an oxidation or a corrosion protection layer can be formed on the surface of structural alloys without building up the concentration of the entire bulk. The ion implantation of alloys provides a unique method of minimizing the use of supply-limited alloying elements without sacrificing on properties (Ref. 24, 25).

(The following projects on Ion implantation are reported in Chapter IV: 5., 6.12, 20.1, 23.3, 25.2, 25.3).

<u>Laser Processing</u>

Besides being of inherent scientific interest, the interactions of intense coherent radiation with materials has long been recognized as a potentially useful technique for materials processing and fabrication. The investigation and development of these techniques has grown as the efficiency and availability of high power lasers has increased. Today, lasers are competitive with many conventional methods, such as cutting, hole drilling, spot welding and transformation hardening. As a close facsimile of the conventional method, the use of a laser for these applications is based on economic considerations.

More recent investigation have sought to exploit the unique properties of laser radiation to provide an all together new capability for surface modifications. In this section several of these techniques, laser surface melting and alloying, and laser shock processing are reviewed insofar as they have potential to improve the crack tolerant behavior of high strength alloys. The power density, interaction time regimes for these and laser processing techniques are indicated in Fig. 11.

Surface Melting and Alloying: Through control of beam intensity and exposure time, the surface layer of an exposed alloy can be melted to a prescribed depth. It has been demonstrated that the precise controlled melting can be used to refine and make alloy additions to the resolidified layer. By this procedure, surface controlled properties such as corrosion, wear, and fatigue crack initiation can be modified without affecting the bulk properties.

Microstructural modifications by laser surface processing depend synergistically on the cooling rate and the alloy additions. As shown in Fig. 11, laser surface melting has been investigated in two power density regimes. The reaction time is obtained by the relative motion of the beam and workpiece, and large area coverage is achieved by sequential scanning of the beam over the workpiece. At high intensity, short time interaction regime melts depths of between 1 and 400 microns are obtained. The melted layer experienced very rapid cooling (10^5 to 10^6 degree C/second) from the quenching action of the substrate materials. In this rapid solidification regime a variety of metallurgical structures have been produced, including amorphous, metastable and supersaturated phases (Ref. 26). Predictably, the melt depths in the long interaction regimes are in the 400 to 2000 micron regime with accompanying corresponding decreases in cooling rate (Ref. 27).

Alloy additions are introduced in laser surface processing by coating the testpiece with the desired elements. Coatings used for this purpose include plasma spray, electroplating, sputtering and powder metals in an organic binding. In the rapid alloying regime, homogenization of the coating and substrate is achieved through some undefined melt pool mixing mechanism (Ref. 28) with diffusion playing a negligible role. At longer exposure times, it is postulate that conventive stirring in the melt pool and diffusion both contribute to homogenous mixing. In the long time exposure regime relative thick cladding can be applied to substrate by selectively melting to the cladding substrate interface (Ref. 29). This procedure allows the deposition of a cladding on a lower melt temperature substrate.

Although numerous investigations on laser surface processing have been reported, property evaluations of the modified layer, with the exceptions of a few cases, have been restricted to metallurgical analysis and hardness measurements. Perhaps the most illustrative example of the potential of laser surface processing is the use of laser meltings to normalize the surface of a sensitized 304 stainless steel (Ref. 30). Through adjusting the cooling rate to avoid a deleterous carbide phase at the grain boundary, the laser processed specimen exhibited a dramatic elimination of intergranular corrosion susceptibility and a much improved resistance to stress corrosion cracking. Evidence has also been reported on the improved stress corrosion cracking resistance of α/β titanium alloy after surface melting (Ref. 31). This study also shows the influence on

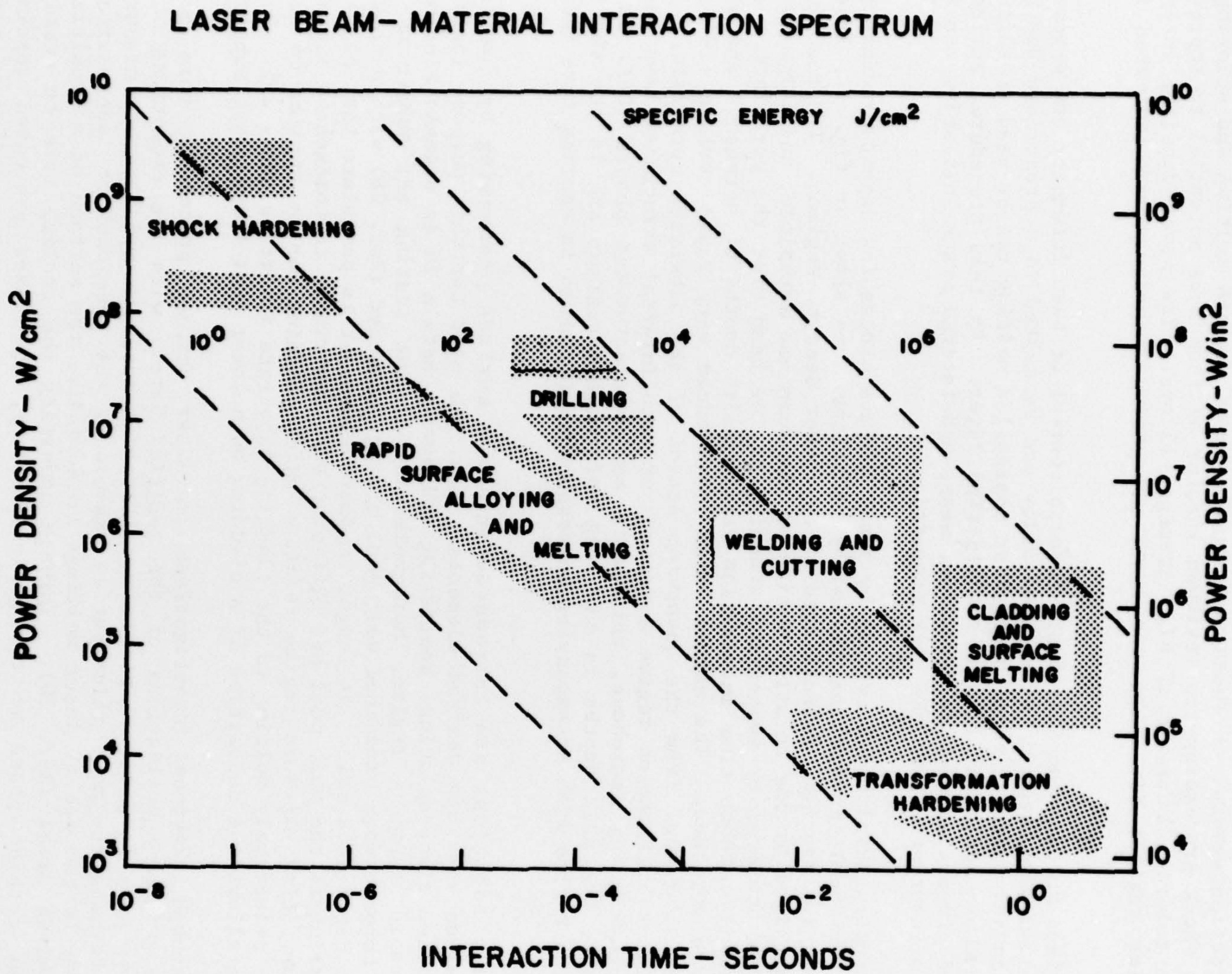

Fig. 11 Power Diversity - Interaction Time Regimes for Various Laser Processing Methods.

residual stress for single, narrow beam layer. Metallurgical analyses of laser melted Zircaloy show promise to reduce the susceptability alloy to stress corrosion cracking although no cracking tests were reported (Ref. 32). In a similarly vain, extensive metallurgical analysis of a series of surfaced alloy AISI 1018 steel also indicate potential improvement in wear and corrosion behavior (Ref. 14).

(The following projects on laser surface processing are reported in Chapter IV: 5.1, 5.3, 5.4, 6.4, 6.6, 25.1).

Laser-Shock Processing: When exposed to the output of a high intensity pulsed laser, typically 10^9 watts/Cm^2 with pulse duration between 20 and 70 macroseconds, stress waves are induced into an irradiated material (Ref. 33). This reaction is generated by the extremely rapid vaporization of the irradiated material and the subsequent expansion of the heated vapor against the target surface. In comparison to the magnitude and velocity to conventional flyer plate generated shock waves, laser induced stress wave should be classiified as weak shock, typically reaching peak pressure of kilobar. Methods of amplifying laser induced stress to high pressures are achieved by placing opaque and transparent overlays of the test piece. It is not clear of the benefits of laser shock hardening relative to other methods of shock hardening and conventional work hardening, although the laser technique has been shown to be a useful method for treating localized or inaccessible areas of components and structures.

Laser-shock processing has been shown to increase the yield strength and to a laser extent the ultimate strength of age-hardenable aluminum weldments, 5086-H32 and 6061-76 (Ref. 34), and of solid solution strengthened aluminum alloys, 7075-76 and 2024-735 (Ref. 35). The fatigue crack initiation resistance, the fatigue crack growth resistance, and the data scatter have been shown to be significantly improved of laser-shock processsing (Ref. 36). Using this technique, data has also been reported on an increased fretting fatigue resistance of 7075-76 foster joints (Ref. 34). The above results suggest the use of laser shock processing to improve the strength and fatigue properties of critical areas of structures, such as welded joints and stress intensity regions.

VI. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

- Through analysis of representative data, the importance of crack tolerant properties of high strength alloys in the design of high performance structures is demonstrated.

- A simple phenomenological description of the failure process of crack initiation, crack growth and fracture provides a useful framework for review of the various approaches to the prediction, control and improvement of crack tolerant behavior of high strength alloys.

- The survey of both journal citations and on-going R&D activities indicate substantive and growing resources directed toward the study of crack tolerant behavior of high strength alloys.

- Many new and innovative approaches to improving the crack tolerant properties of high strength alloys has been identified, including the potential to optimize independently the bulk and surface controlled properties.

- Powder metallurgy is identified as a major R&D thrust within DoD for improving crack tolerant behavior and lower fabrication cost of high strength alloys.

- Review of available data demonstrate that ion implantation provides a technique to improve significantly the surface properties alloys, including their fatigue, wear and corrosion behavior.

- Published results also indicate that laser processing offers a potentially useful method for surface modifications of alloys although evaluation of modified properties has been limited.

- R&D opportunities and trends identified in this report are forecasted to be aggressively pursued over the next 2 to 3 years and such be closely monitored by P-1.

- Recommendations for expanded P-1 activities in this area include:

  - conduct 1-day symposium during CY-80 annual meeting of P-1.

  - initiate cooperates program in service evaluation of ion implantation and laser modified surfaces for military applications.

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